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EXPERIMENTAL AND NUMERICAL VERIFICATION OF 3D FORMING

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ABSTRACT

Motivated by sustainability arguments there is a recent interest in forming of advanced structures in paper and paperboard. Therefore, in this paper, hydro-forming of papers and the effect of different fibre raw materials, beating, strength additives (PVAm), grammage and wet and dry papers have been investigated experimentally and numerically.

The experiments were carried out in laboratory hydro-forming device. Softwood sheets performed better than hardwood sheets, since they had higher strain at break. The ability of paper to withstand hydro-forming successfully was primarily dependent of the strain at break of the paper in relation to the straining required to fill the mould. Forming of wet sheets were also investigated; overall the wet sheets formed better than the dry sheets, which was due to higher strain at break and lower elastic energy. Since the forming was displacement controlled, there was no significant difference in the effects of beating, amount of PVAm or grammage.

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Finite element modelling was performed to identify local strains and predict problematic regions. Simulations were also performed to determine how anisotropic sheets would behave, as well as to compare the process of hydro-forming with press-forming. The papers could be strained to higher strain levels than the measured strain at break because the paper is supported by the membrane and mould during the forming operation. The maximum strain a paper can withstand can be increased if the paper can slide into the mould, i.e. by having a lower coefficient of friction between the steel mould and the paperboard.

During hydro-forming the paper is supported by a rubber membrane, which gives lower strain levels than the corresponding press-forming operation due to the difference in how the paper is deformed. Press-forming therefore required paper with higher strain at break. Higher friction results in more paper being pulled into the mould, which contributes to wrinkling of the paper. Simulation of tray forming of a creased sample was performed, which showed that high friction or compliant creases decreased the circumferential compression.

INTRODUCTION

The ability to form complex paper and paperboard structures is an area in which there has been a growing interest from both converters and board manufacturers. To be able to extend the market into areas currently dominated by plastics, smooth double curved surfaces should be produced in a fast and reliable manner. Three obvious uses for such surfaces are as food containers, such as trays, inlays in packaging to protect and display products, e.g. consumer electronics, and attractive primary packaging. In the forming of double curved surfaces two strategies are used. Either a wet pulp can be sprayed onto a mould; or an initially flat paper structure can be converted into a complex shape. The latter is advantageous since paper then can stored as dry rolls prior to converting. This is the procedure that will be investigated further here. Apart from creasing and folding, there are three main methods that are currently explored for producing advanced shapes of dry paper and paperboard. These are press-forming, [1], hydro-forming [2,3] and deep-drawing, [4]. In short; press forming utilizes a solid male and female die to form a paper blank; for hydro forming, the male die is typically replaced with a pressurised membrane; in deep drawing a male punch pushes the paper blank through a hole. Most commonly used today is press-forming which often is done on creased samples to form trays and plates. Using the different forming techniques paper structures will be converted into different shapes. However, the loading of the paper can be different depending on the converting technique. Because of this different part of the structure will deform differently.

Finite element simulations are commonly used in other industries such as aviation, automotive, nuclear and materials in general. However, in the paper industry the finite element tool is not yet commonly used in product development of paper and paperboard qualities. One of the main reasons for this is the extreme anisotropy in paper. In the scientific literature related to the development of finite element simulations much focus has been put on the development of material models and the identification of required material properties, see e.g. [5, 6, 7, 8, 9, 10]. These works include development of both continuum and interface material models. By using models knowledge about deformation mechanisms in paper converting finite element simulations can be used to study the forming processes. Finite element simulations have previously been used to study creasing [11, 12, 13] and folding operations [14,15], the short compression test [15, 16,17] and also 3D forming [18, 19, 20]. These simulations have supported the identification of which material properties that affect the different converting operations.

In this work aspects of hydro-forming, such as the effects of different fibre raw materials, beating, strength additives (PVAm), grammage and dry content (wet to dry), will be explored. Finite element modelling was performed to identify local strains and localise problematic regions. Simulations was also performed to determine how anisotropic sheets would behave, as well as to compare the process of hydro-forming with press-forming.

MATERIALS

Isotropic hand sheets were produced using bleached hardwood or bleached softwood fibres. The fibres were beaten in full commercial scale at the Iggesund mill (Holmen, Sweden), where the softwood pulp was beaten to 16 °SR or 19.5 °SR, and the hardwood pulp was beaten to 18.5 °SR. To the softwood pulp 0, 6 or 10 g/kg PVAm was added as a strength additive; while 0 or 10 g/kg were added to the hardwood pulp. PVAm was originally used primarily as a wet strength agent, but has been shown to increase the dry strength of paper as well [21]. Both 80 g/m^2 and 160 g/m^2 sheets were made. In the experimental procedure, the sheets were either tested wet or dry. A summary of the different parameter combinations investigated is given in Table 1.

Table 1. Sheets tested in the forming equipment. Testing was done either wet or dry

	Softwood (S)					*Hardwood (H)*	
	Low beating		*High beating*				
PVAm [g/kg]	0	10	0	6	10	0	10
80 g/m^2	Dry	Dry	Dry, Wet	Dry	Dry, Wet	Dry	Dry
160 g/m^2	–	–	Dry, Wet	–	Dry, Wet	Dry	Dry

EXPERIMENTAL SETUP

The sheets were formed in a hydro-pressing equipment developed and tested by Mozetic [22]. The apparatus has previously been used by Östlund *et al.* [2], Svensson *et al.* [23] and more recently by Linvill and Östlund [3]. In the apparatus three different moulds were used, as shown in Figure 1. The moulds were chosen to have increasingly advanced shapes. For each sheet type and mould two dry sheets were tested. This was done with conditioned sheets in a controlled environment at 23°C and 50 % RH.

Double-curved paper structures were formed by putting paper blanks on top of the mould. A paper specimen that was larger than 150 cm in diameter was used in all cases; such that it was fixed by a blank holder metal ring and clamped with a constant pneumatic pressure (6 bar), see Figure 2. Above the paper there was a rubber membrane. During forming air was let into the apparatus such that the membrane presses the paper towards the mould.

The dry sheets (Table 1) were placed in the mould that was heated to 110 °C, and the blank holder was tightened. This held the edges of the sample with a constant force and the membrane was inflated to 3 bars. The forming pressure was kept for approximately 5 seconds before the process was reversed and the formed sample was retrieved.

The wet sheets (Table 1) were formed press dry, which here means a moisture ratio of about 40 %. In this case, the process was the same as for the dry samples,

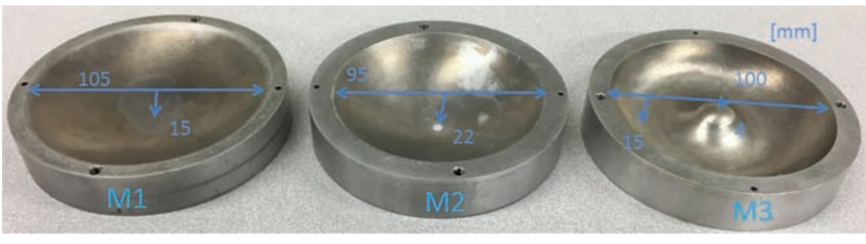

Figure 1. The three moulds M1, M2 and M3 which had increasingly advanced geometries, resulting in higher demands on the paper being formed. The widths and depths are indicated in the photo.

Figure 2. The forming equipment used to hydro-forming paperboard structures using the moulds in Figure 1.

except that for these sheets the forming pressure was kept for 10 minutes, to allow the sheets to dry in the mould.

The different sheets will in the presentation of the results be referred to by an index composed of fibre-type: hardwood (H), softwood (S), degree of beating: high (H) or low (L), grammage (80 or 160) with a superscript indicating the amount of strength additive (0, 6, 10 g/kg), thus $SH80^0$ is an 80 g/m^2 sheet, made of highly beaten softwood pulp without strength additives. The moulds will be referred to as M1, M2 and M3 corresponding to the moulds from left to right in Figure 2.

EXPERIMENTAL RESULTS

Forming of double curves surfaces

For each forming condition listed in Table 1 two sheets were used in the forming of double-curved surfaces. In Table 2, the results of the forming have been listed, where the numbers 0, 1 or 2 indicates how many successfully formed sheets that

Table 2. Results from the forming trials. The results are indicated by a three-number code that indicates if 0, 1 or 2 forming attempts where successful. The first number corresponds to M1, the second to M2 and the third to M3. A bar chart of the results for the M1 and M2 moulds can be seen in Figure 3

		Softwood (S)					*Hardwood (H)*	
		Low beating		*High beating*				
	PVAm [g/kg]	0	10	0	6	10	0	10
80 g/m^2	Dry	2,0,0	2,0,0	2,0,0	2,0,0	2,0,0	2,0,0	1,0,0
80 g/m^2	Wet	–		2,2,0	–	1,0,0	–	–
160 g/m^2	Dry	–	–	2,0,0	–	2,0,0	0,0,0	0,0,0
160 g/m^2	Wet	–	–	2,1,0	–	2,1,0	–	–

were produced. Each mould is indicated in the table, where the first number corresponds to M1, the second to M2 and the third to M3. The results for M1 and M2 are also summarized in Figure 3.

The dry sheets could only be successfully formed in the mould with the shallowest geometry (M1), while wet sheets could form well in the two moulds M1 and M2. It should be noted that no sheets could be formed in mould M3. All dry sheets showed signs of wrinkling beneath the clamping ring, while the wet samples did not. This would indicate that the paper was pulled down into the mould during the forming operation, which will help decrease the straining in the paper. Since the elastic modulus of the dry sample is higher than the wet samples, the straining during dry forming will generate more elastic energy that contributes to severe cracking of the formed surfaces. In the wet samples cracks have a local character, and the forming contributes more to thinning of the paper.

Overall, the dry softwood sheets formed better than the dry hardwood sheets. It was possible to use mould M1 for both fibre types, but only the softwood sheets could be formed in mould M2. The reason behind this was that the strain at break in the hardwood sheets were not high enough to enable forming in the M2 mould. There were no significant effects on the forming result, due to the two degrees of beating, the amount of PVAm or the grammage.

Typical images of formed samples can be seen in Figure 4, and, in addition, in Appendix 1 photos of all tested configurations can be found. The images in Figure 3 were taken from highly beaten 160 g/m^2 softwood samples without strength additives and are typical of the results from the forming. No other qualitative evaluation was performed on the hydro-formed sheets.

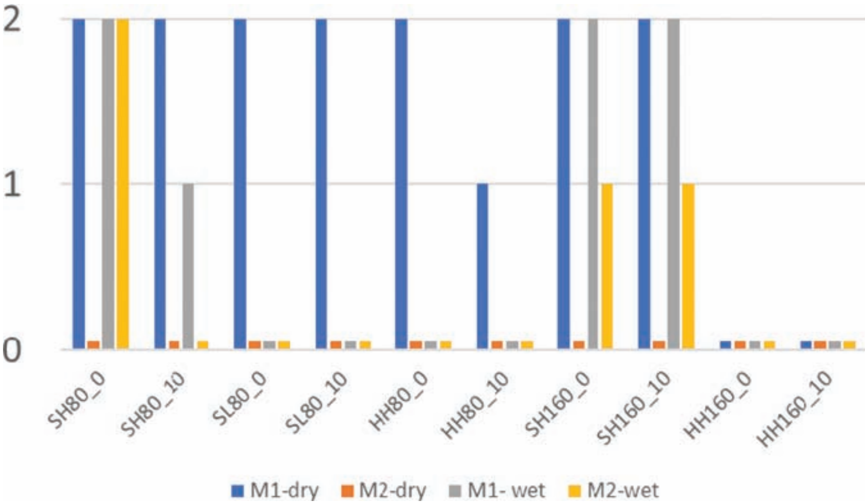

Figure 3. The results from the forming trails for M1 and M2, the bar chart displays the number of successfully formed sheets (out of two) for each sheet type.

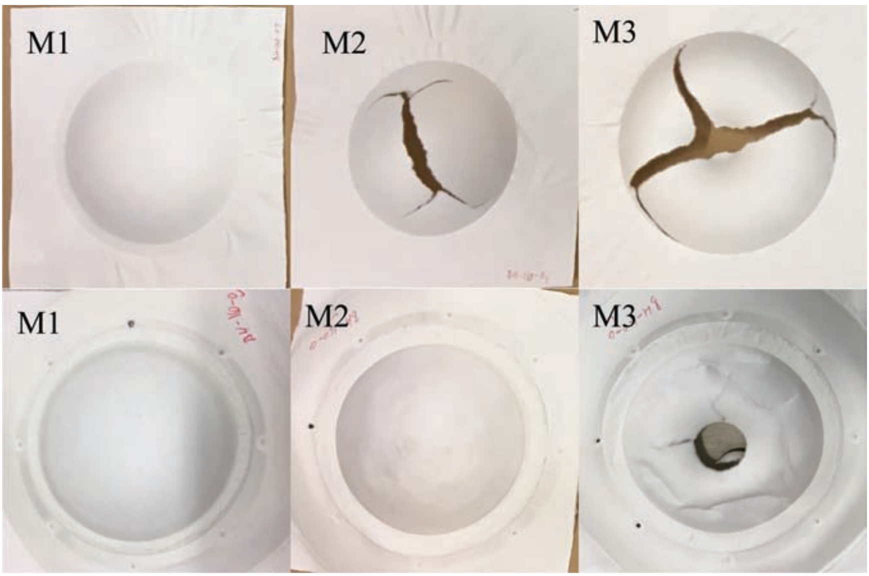

Figure 4. Images of 160 g/m^2 softwood, highly beaten, samples without strength additives. Top row is dry formed sheets, bottom row is wet formed. The images are typical of results from forming using Moulds M1, M2 and M3.

Tensile testing

The tensile testing brings insight into the material properties of the sheets, and can be compared to the results from the forming experiments. Standard tensile tests, using an L&W Alwetron (ABB, Lorentzen & Wettre, Stockholm, Sweden), were performed on dry sheets (sample width 15 mm, length between clamps 100 mm, strain rate 100 mm/min, clamping pressure 6 bar). Tests samples were taken out in orthogonal directions. To calculate the stress from the measurement the structural thickness was measured for all papers.

In Figures 5 and 6, the strain at break and strength of the different paper qualities are shown. For the highly-beaten pulps, the strength additive had only a minor effect on the tensile properties, while the tensile strength increased well over 10 % with increased PVAm dosage for the paper with low beating. The strength additive did, however, not affect the strain at break. All the softwood papers had similar strain at break, between 4 and 5 %, while the hard wood papers had a lower strain at break between 3 and 4 %.

Tensile tests were performed on wet sheets from highly beaten softwood sheets without strength additives. Both 80 and 160 g/m^2 sheets were tested using the Alwetron, with wider samples (50 mm) and lower clamping pressure (2 bar). This testing showed that the tensile strength was 0.66 MPa for the 80 g/m^2 sheets and 0.36 MPa for the 160 g/m^2 sheets. The corresponding strain at break was 7.8 % and 8.0 %, respectively. Hence, having wet sheets the strength decreases to about 1/10 of the dry strength, while the strain at break increase by a factor 2.

Short tensile tests

Short span tensile tests [16, 24] were performed on the sheets prior to forming. In addition, testing of formed double curves surfaces were done. In this case samples were taken from the three moulds M1, M2 and M3. The tests were performed on 160 g/m^2 sheets of highly beaten softwood without strength additives. Testing was done in a MTS tensile tester, using 15 mm wide samples with a clamping length of 5 mm and a strain rate of 5 mm/min. Only one sample was cut-out from each double curved surface. The samples were located about 2/3s of the radius in from the edge of the mould and aligned along the radial direction. An example of the sample location can be found in the inset in Figure 7.

The results from the short span tensile tests showed that the strength and stiffness of the dry formed sheets were higher in the formed double curves surface than in the unformed reference sheet, see Figure 7. The wet formed sheets possessed lower strength and stiffness than the dry formed and reference sheet.

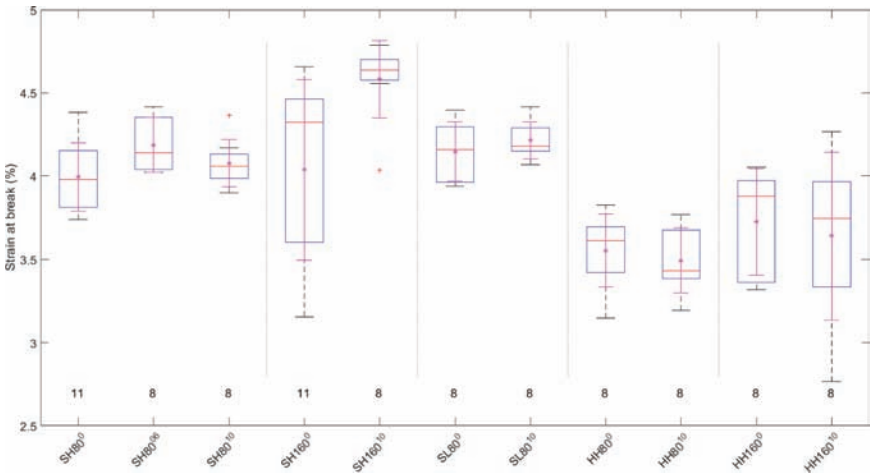

Figure 5. Boxplot of the strain at break from standard tensile tests on the different paper qualities (dry, unformed). The red bar indicates the median value, the blue box spans between the 25 and 75 percentiles, the black bars indicates extreme values, red + are outliers. The magenta dot is the mean value, and the magenta error bar indicate ± one standard deviation. The numbers under the boxes indicates how many samples that were tested and the black dotted lines separates different sample types for increased readability.

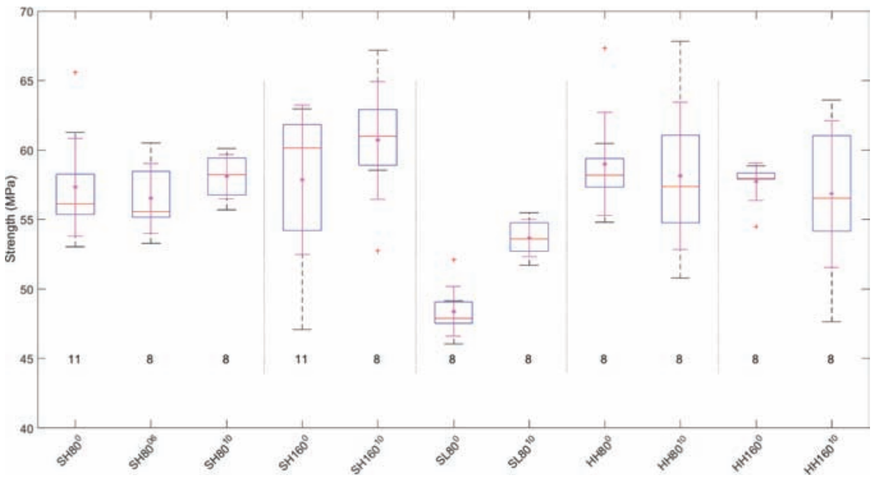

Figure 6. Boxplot of the strength of the samples from standard tensile tests on the different paper qualities (dry, unformed). See Figure 7 for details about the graph.

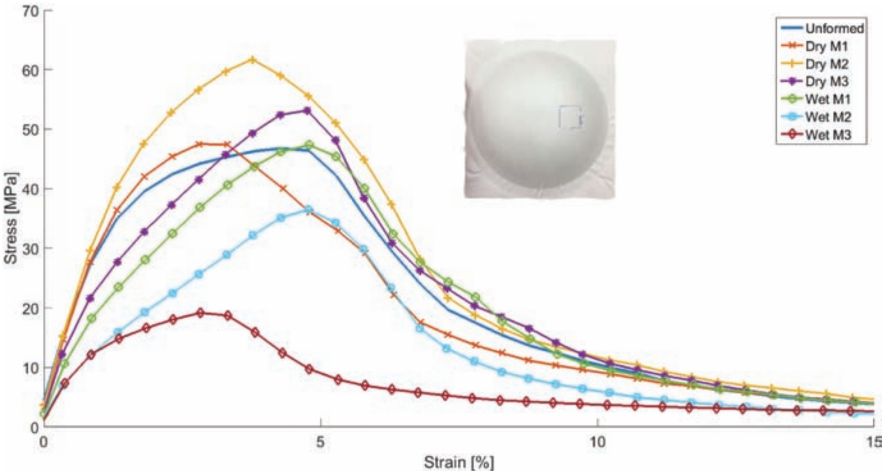

Figure 7. Stress strain curves from short span tensile tests performed on 160 g/m^2 sheets of highly beaten softwood without strength additives. An example of where the samples were extracted is inset next to the legend.

This would indicate that forming moisture and temperature was not sufficient to generate as many bonds as during conventional drying, i.e. in the dry sheets.

For the dry sheets, it could also be observed that highest strength was achieved in mould M2. Hence, the fibre network has been stretched ideally in this mould without failing, which also increases the tensile strength considerably. It should be remembered that the M3 mould failed, and hence the network was stretched too far.

FINITE ELEMENT ANALYSIS

To evaluate the magnitude of the strains needed to fill the moulds, and to investigate how the filling occurred, finite element simulations were carried out. The three moulds (M1, M2 and M3) were simulated as quarter models in Abaqus Explicit [25]. The different models with meshes are shown in Figure 8. In the simulations, only the forming step was simulated and not the release of the pressure. The moulds and blank holder was simulated as discrete rigid bodies, since they were much stiffer than the paper. The blank holder was put in contact with the paper and thereafter held stationary at a constant distance from the top surface of the female mould. The contact conditions between paper and both blank holder and mould was defined using hard contact in the normal direction and penalty

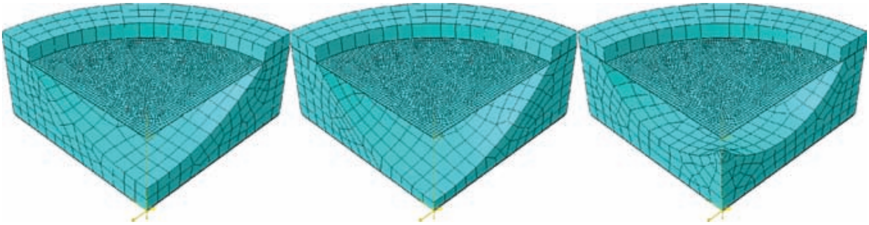

Figure 8. The finite element meshes of the papers and the three moulds, from left to right M1, M2 and M3.

Table 3. Material parameters used in the simulations

Material model		*E (MPa)*			*ν*			*G (MPa)*		*σ^y*
Isotropic models											
Elastic		4000			0.3			–		–	660
Elastic-plastic		4000			0.3			–		40	660
Orthotropic model											
	MD	*CD*	*ZD*	*MDCD*	*MDZD*	*CDZD*	*MDCD*	*MDZD*	*CDZD*		*Density*
Elastic-plastic	5920	2670	228	0.45	0	0	1431	60	60	40	660

friction in the tangential directions, with a coefficient of friction of 0.1. The paper was simulated using five layers of 8 node linear brick continuum elements, with reduced integration and hourglass control. The membrane was not simulated, but was instead replaced with a homogenous pressure (10 bar) over the entire membrane surface. Three different material behaviours were investigated: isotropic elastic, isotropic elastic-plastic with perfect plasticity and orthotropic elastic-plastic with perfect plasticity. The isotropic material constants were set to resemble the material properties seen in the lab-sheets, while the anisotropic behaviour was based on a top layer from a commercial multi ply paperboard [14]. The material properties can be found in Table 3. All models were mass-scaled to an increment size of 10^{-5} s.

RESULTS AND DISCUSSION

The models were used to estimate the strain levels that could be expected during forming and the filling of the moulds.

Strain levels during forming

In Figure 9, elastic strains in one direction for the three moulds are shown. Although this is a limited measure, it is comparable with the measured strain at break from the tensile tests, c.f. Figure 5. The elastic simulations indicate that M1 has a maximum in-plane strain of around 5 %, M2 up to 10 % and M3 well over 15 % (23 % at the tip). Note, that the strain fields in the paper sheets are not uniform. Hence, the strain at break in mould M1 is already at the limit of what could be possible to achieve with the papers, and moulds M2 and M3 far exceeds the strain at breaks in Figure 5. Yet it was observed that all papers, except the 160 g/m^2 hardwood papers, could be formed in mould M1, c.f. Table 2. The main reason that some papers can be formed although it exceeds its strain at break, was that the paper is partly supported by the mould during the forming. Hence, the elastic energy stored in the paper is minimized, which prevents severe cracking, as illustrated by the fact that 80 g/m^2 hardwood papers could be formed using mould M1 but not the 160 g/m^2 papers. In addition, for wet paper it was previously concluded that the strain at break increased by a factor of two while the strength dropped. The mechanism behind this is likely that the deformation is homogenized over the specimen. When the wet papers were formed, it was possible to successfully make double-curved surfaces of softwood in mould M2.

For the M2 mould simulations with an isotropic and orthotropic elastic-plastic material, the contour plots can be seen in Figure 10, here the maximum strains are well over 15 % for both simulations. Especially the orthotropic model showed large strains at the bottom of the mould. When the material is orthotropic the strain in the more compliant CD direction will become higher, which contributes to the higher total strain in the model. Hence, for orthotropic papers where the properties in MD and CD differ there are two possible routes to enable forming of double curves surfaces. First, the strain at break in CD can be increased to comply with the strains that develop in the mould. Alternatively, the stiffness and strength in CD can be increased, which will bring it closer to the isotropic case. Lowering the stiffness in MD would also make the sheet more isotropic. Which

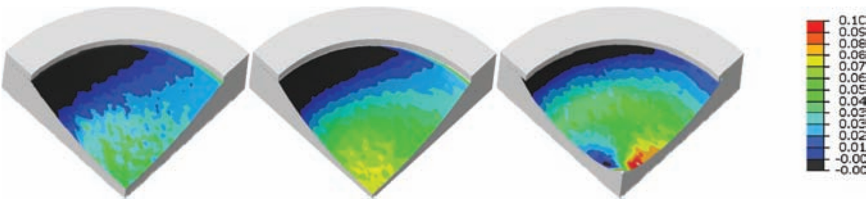

Figure 9. The strain in one material direction (oriented along the right edge in the picture) for the 3 original moulds: M1, M2 and M3 simulated with an isotropic elastic material.

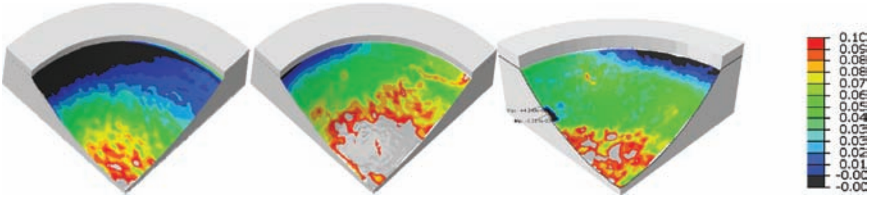

Figure 10. The M2 mould simulated with an isotropic elastic-plastic material (left) and an orthotropic elastic-plastic material (middle and right). The orthotropic model is shown with in-plane strains in the two directions (middle: MD, original orientation along the right edge, right: CD, original orientation along the left edge).

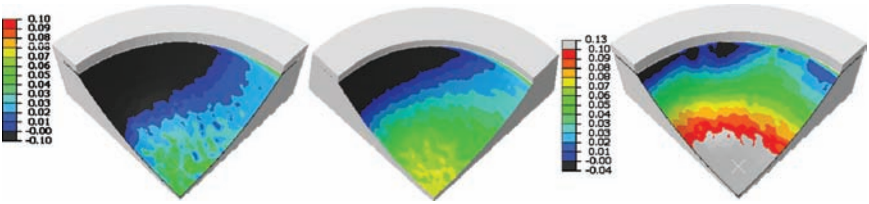

Figure 11. Effect of friction on the strain. From right to left, friction coefficient 0.01, 0.1, 0.3. Lower friction results in more material entering the forming area which in turn results in lower radial strains, but higher need for circumferential compression.

route to choose is partly dependent on how it would affect the interplay with the friction.

The effects of friction on the strain levels in the paper have been investigated. Two simulations based on the elastic model of forming using mould M2 were performed, where the friction coefficients were 0.01 and 0.3 respectively. The coefficients were chosen to be high or low enough to cause a clearly changed behaviour. From the simulations, as shown in Figure 11, it could be concluded that the lower friction allows more material to enter the mould during forming. This leads to lower tensile strains in the radial direction, but the increased amount of material requires the paper to become compressed in the circumferential direction. This would cause increased wrinkling of the paper. When the friction was increased, less material entered the mould, and hence resulted in higher radial strains.

When comparing the tensile data from the dry sheets with the results from the forming trials it was apparent that the forming was limited by the strainability of the paper rather than the strength of the papers. This also explains why adding the strengthening agent had no significant effect on the on the forming as it mainly affected the strength.

Filling of the moulds

In Figure 12, a side cut of the paper during different stages of the forming process is shown for moulds M1, M2 and M3 respectively. The images were extracted from the elastic models. In the figures, it was apparent that the filling of the moulds started at the edge and progressed inward for moulds M1 and M2. Mould M3 started to fill in a similar manner, but the added complexity of the shape, causes the paper to touch the middle of the mould before it was filled completely. When the middle of mould M3 is in contact with the paper, the paper will be strained differently. This highest strain levels will hence arise on the slope of the middle section, while it is always in the centre for moulds M1 and M2.

Based on the filling behaviour of the moulds seen in Figure 12, it can be concluded that friction mainly plays a role for the paper that is clamped between the blank holder and mould, since the rest of the paper only gradually meets the mould. In mould M3, the middle of the paper reaches the mould earlier, but at a symmetry point which means that there is little material that is free to move. Thus, friction between mould and paper is mainly of interest for the dry papers, as the wet papers can be fixed by the clamps. If the friction and/or blank holder force is sufficiently low, some paper can be fed into the mould during forming which would lower the required strain but in turn result in wrinkling. This in turn requires that the stiffness of the paper is high enough to overcome friction instead of straining the sheet. From Figure 4 it is apparent that some wrinkling has occurred for the dry sheets. The friction would play a larger role for both wet and dry papers when using a male die for the forming.

Comparing press-forming and hydro-forming

Two additional models were analysed in order to investigate how press-forming differs from hydro-forming. First, forming using mould M2 was simulated, but instead of using a membrane a rigid male die was used to press the paper, as shown in Figure 13. In the first model, the same isotropic elastic material properties and interactions as the hydro-forming model was used, while the added male die was modelled as a discrete rigid body.

The results from the model using a male die instead of a membrane can be seen in Figure 14. It is observed that the strain in the model were over 10 % in the centre of the mould, compare the 8% that was required for hydro-forming in Figure 9. Further this mould was filled differently than the membrane model. The centre of the paper was pressed down continuously by the male die, which first bent the paper and then forced it out towards the female mould. Hence, this suggests that press forming will require paper with higher strain at break than hydro-forming.

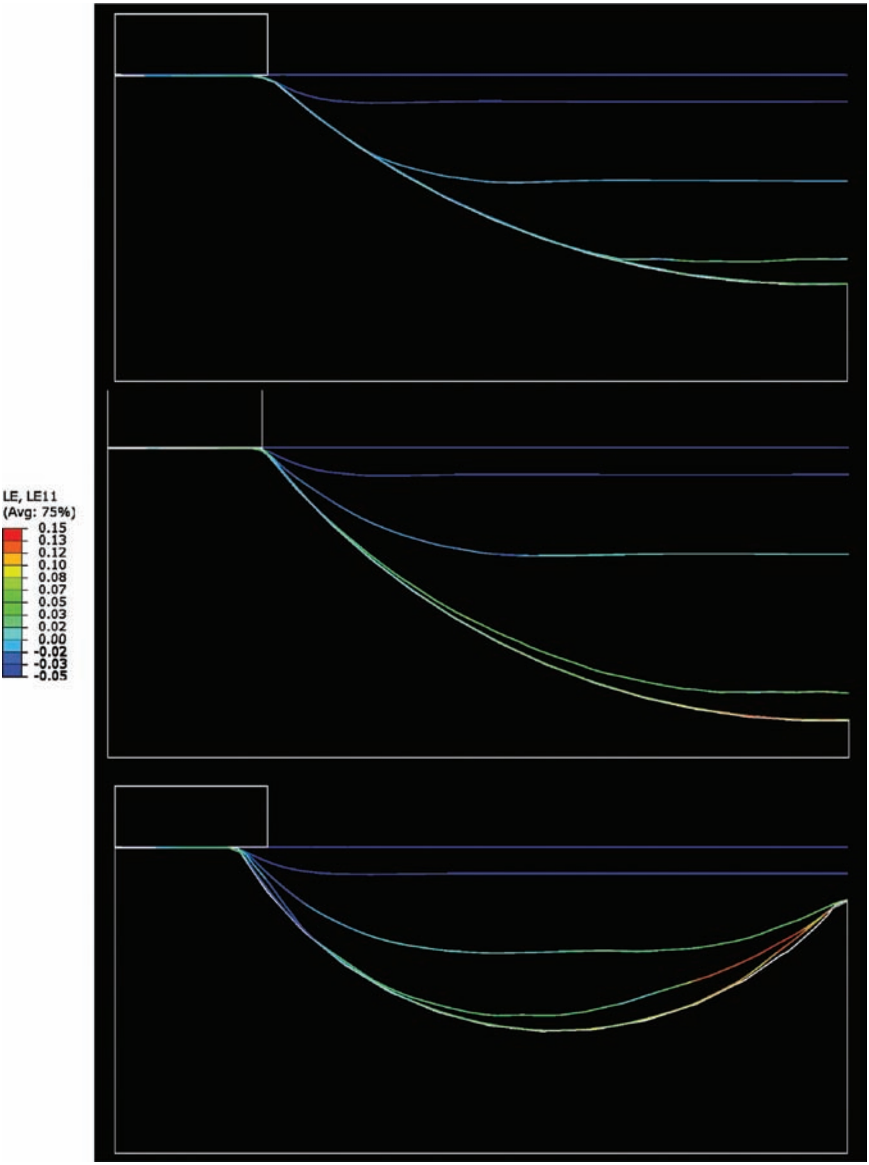

Figure 12. The position of the paper contra the moulds at different stages of the forming. Based on the isotropic elastic simulations. From top to bottom M1, M2 and M3.

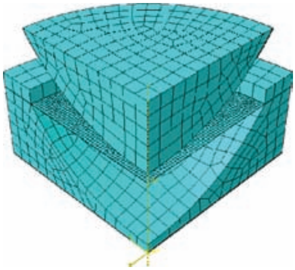

Figure 13. The finite element mesh of the rigid bodies and papers used simulated press-forming.

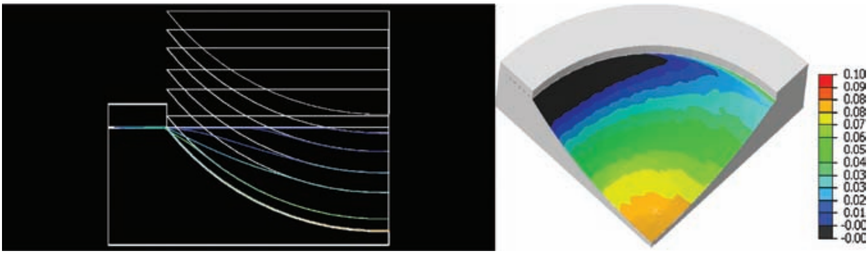

Figure 14. The paper movement during forming and the final strain distribution for M2 using a male die instead of hydro-forming.

Also, for press forming the effect of friction was investigated. The results from three simulations, with three different coefficients of friction, 0.01, 0.1 and 0.5, can be found in Figure 15. The same general trends as for hydro-forming were seen, but the male die resulted in some differences. Since the material was in contact with the male die, the friction between die and paper affects how the paper could move/slide along the surface of the die. With a low friction coefficient, the behaviour is similar to what was observed in the hydro-forming simulations. When the friction was high the paper was prevented from sliding, which causes the strain to be more evenly distributed. For a high friction coefficient, this results in lower peak strains although less material could enter the mould.

The simulation of forming using a male die showed that the friction between the die and the paper would play a larger role as the paper was in contact with the die during the whole forming step. A higher friction between the male die and the paper resulted in a more uniform straining for this geometry. The strains from this simulation were higher than what was for the hydro-forming.

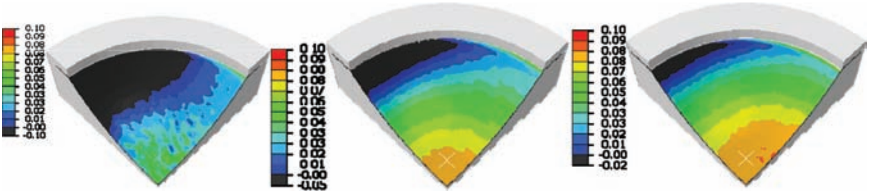

Figure 15. Effect of friction on the strain. From right to left, friction coefficient 0.01, 0.1, 0.5. Lower friction results in more material entering the forming area which in turn results in lower radial strains, but higher need for circumferential compression. In the high friction simulations, the material cannot slide along the male die as easily, which spreads the straining more evenly.

Simulation of tray forming

The second simulation performed was tray forming of a creased sample. The tray forming model used discrete rigid bodies for the blank holder, male and female dies. The model is shown in Figure 16. In this case, a creased paperboard sample was formed. The sample had creases that were distributed along the corner of the tray, see Figure 16. These creases were model in such a way that the cross-crease material response could be set to be much more compliant than the surrounding paperboard. The behaviour along the crease was calculated to be similar to the surrounding paperboard. In this way, the modelled creases emulate how the paperboard folds or wrinkles along the creases during the forming operation. The orthotropic elastic-plastic material model in Table 3 was used to represent the paperboard properties.

In Figure 17, contour plots of the second principal strain from three simulations of tray forming with different friction coefficients (0.01, 0.5 0.1) are shown. This the second principal strain-measure was chosen because it roughly follows the circumference of the tray. The results are all taken at the end of the punch down stroke. For all four models, contours within the creases has been left out, since this makes it easier to evaluate the behaviour of the paperboard response. In the simulations in Figure 17, the cross-crease properties were the same as the paperboard properties, corresponding to an un-creased or lightly creased paperboard.

The effect of different friction coefficient was similar to the previous simulations; a low friction enabled more material to enter the moulds, which would result in wrinkling due to large circumferential compression. A high friction coefficient reduces the circumferential compression, but in turn cause unacceptable high tensile strains, which are not shown in Figure 17.

The point of the creases is to absorb the circumferential compressive strain. To better represent this behaviour in the simulations, the stiffness in the direction

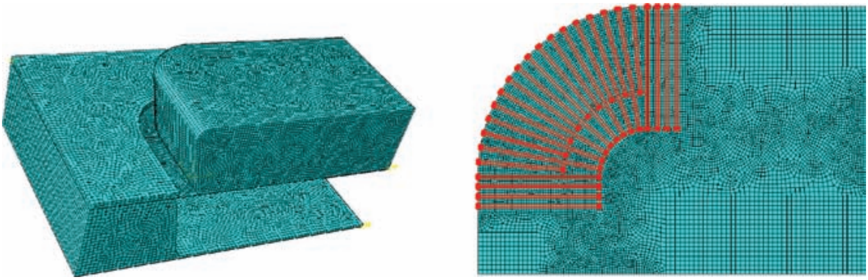

Figure 16. The finite element model of the blank holder, female die, male die and paperboard used to simulate tray forming. Right picture is the mesh of the paperboard, where the creases has been highlighted.

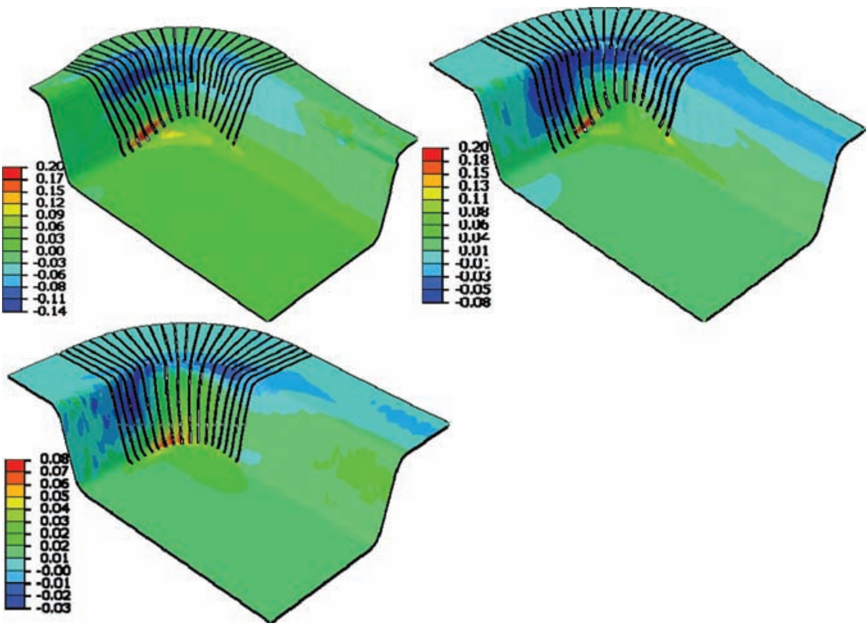

Figure 17. The effect of friction. From top left: Low coefficient of friction (0.01), medium coefficient of friction (0.1) and high coefficient of friction (0.5), between rigid tools and the paper, for these simulations the cross-crease stiffness was the same as the paperboard.

across the crease was set to 10% of the stiffness of the paperboard, compare Table 3. All properties along the crease was however the same as the paperboard. A comparison of the simulation with friction coefficient 0.1 in Figure 17, and the same model with lower crease compliance in Figure 18 shows that the model behaves differently with decreased crease compliance. When the crease stiffness was decreased, the creases took larger deformations, and the end of the creases maintained in the bottom of the corner, which was not the case in Figure 17. Although the maximum compressive strains were of similar magnitude, the model with lower crease stiffness showed a more even strain distribution, and lower strains in the tray corner.

Apart from wrinkling caused by excess material, another problem during tray forming is cracking. The models indicate areas of large tensile strains, see Figures 17 and 18, at the corner of the tray, close to the end of the creases. This corresponds well with the areas where cracks normally appear during tray forming. Thus, this model shows potential as a tool to explore the effects of friction and positioning of creases in order to optimize the tray forming process.

Hydro-forming is an interesting forming method for paper and paperboard. It does however set demands on the strain at break of the paper. These demands are hard to meet with conventional paper qualities, at least when dry. Wet papers are better suited for forming from a material point of view, but impractical from a commercial one. One possibility might be re-wetted papers, something that should be explored in future work.

Finite element models of the forming process are useful for determining the unseen behaviour of the paper during forming as well as estimating the strains needed for successful forming. It further allows for exploration of the effect of different

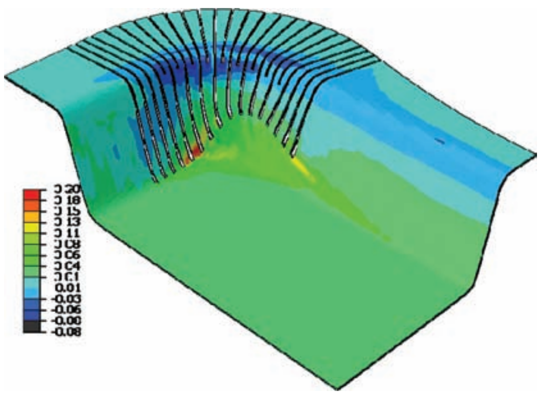

Figure 18. The effect decreased cross crease compliance, which was 10% of that of the paperboard, and the friction between tools and paper was 0.1.

properties of the process such as the effect of friction. It should be noted that even though hydro-forming differs from other types of forming, some aspects are still similar. Thus, solutions found for one type of forming may be applicable to other.

CONCLUSIONS

Dry lab sheets made of either softwood or hardwood fibres were formed into double curves surfaces using hydro-forming. The softwood sheets performed better, since they had higher strains at break. The ability of paper to withstand hydro-forming successfully was primarily dependent on the strain at break of the paper in relation to the straining required to fill the mould. Forming of wet sheets were also investigated; overall the wet sheets formed better than the dry sheets, which was due to higher strain at break and lower elastic energy. Since the forming was displacement controlled, there was no significant effect of beating, amount of PVAm or grammage.

Finite element models were used as a tool to evaluate the hydro-forming process and to indicate how different values of parameters will affect the outcome. The effect of strain levels during forming and how the moulds were filled were investigated. The papers could be strained to higher strain levels than the measured strain at break. This was since the paper was supported during the forming operation. Due to the friction against the mould, the papers were strained gradually, which prevented strain localization. The friction further counteracted the elastic energy contained in the paper. The maximum strain a paper can withstand can be increased if the paper can slide into the mould, i.e. by having a lower frictional coefficient. The trade-off being increased risk of wrinkling as well as increased strain localization.

During hydro-forming the paper is supported by a membrane, which gives lower strain levels than a corresponding press-forming operation. Press-forming therefore requires paper with higher strain at break. Higher friction results in more paper being pulled into the mould, which contributes to wrinkling of the paper. Simulation of tray forming of a creased sample was performed, which showed that increased friction and compliant creases reduced the circumferential compression in the paperboard outside of the creases.

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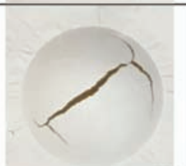
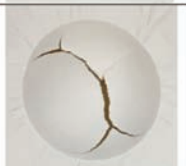
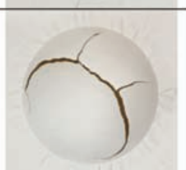
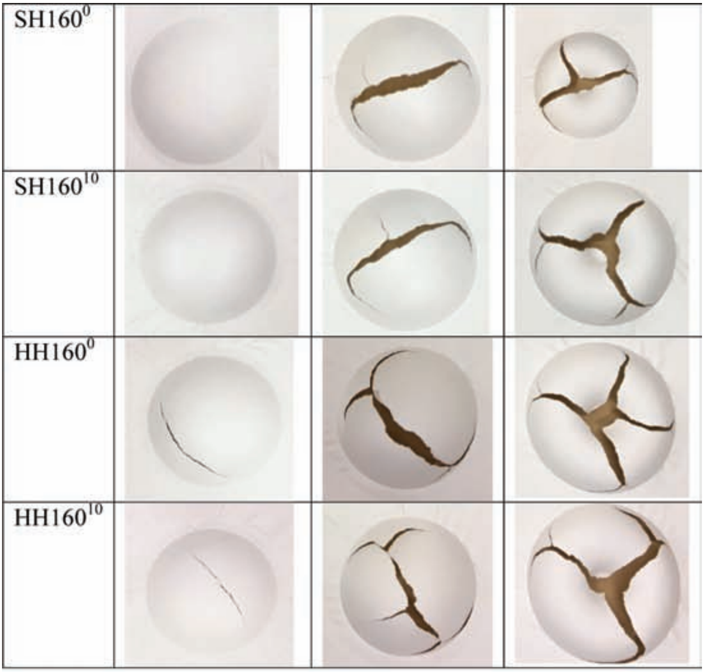
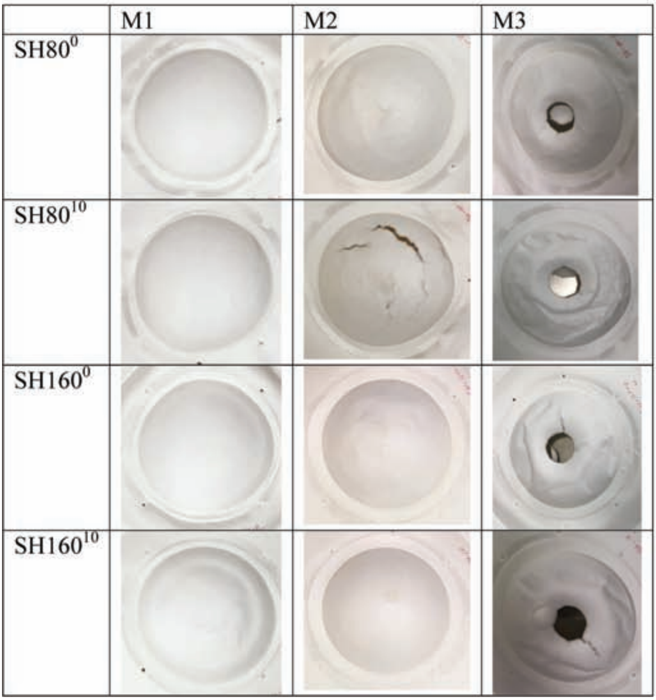
APPENDIX 1

Photos of double curves surfaces

	M1	M2	M3
SL80^{0}			
SL80^{10}			
SH80^{0}			
SH80^{6}			
SH80^{10}			
HH80^{0}			
HH80^{10}			


SH160^{0}
SH160^{10}
HH160^{0}
HH160^{10}


M1
M2
M3
SH80^{0}
SH80^{10}
SH160^{0}
SH160^{10}

Transcription of Discussion

EXPERIMENTAL AND NUMERICAL VERIFICATION OF 3D FORMING

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[4] Stora Enso
[5] Royal Institute of Technology, KTH
[6] BiMaC Innovation

Eric Linvill WestRock

I am familiar with this topic as you know. You started off by saying you looked at two different beating levels.

Anton Hagman RISE BioEconomy and BiMaC Innovation

Yes.

Eric Linvill

What were they?

Anton Hagman

I don't have the numbers exactly in my head, but they are stated in the article. I think the higher one was around 18 degrees SR.

Discussion

Eric Linvill

Secondly, what is the strain measure that you are using? Since you have large rotations there, are you taking into account these large rotations?

Anton Hagman

Yes.

Eric Linvill

Okay, because that could vary drastically and effect results. Thanks

Andre Phillion McMaster University

Very nice work. It reminded me a lot of something called forming limit diagram which is used in metallurgy to look at how much you can deform metals in biaxial tension, so I am wondering if you tried putting a grid on your dry samples so that you could perhaps validate the mechanical model that you used in the simulations against your experimental data.

Anton Hagman

I haven't done it. I have thought about doing it. Eric, who talked previously, did something like that. We would like to do it, but, if I remember correctly from Eric's work, it wasn't as straightforward as one might think. Preferably since I am usually doing things with digital image correlation, I would have wanted to see how it looked and follow it, but it's hard to do when you have aluminum moulds.

Ville Leminen Lappeenranta University of Technology

I was wondering if you took into account the blank-holding force and the sliding of the material into the mould, or did you just simulate the rigid clamping?

Anton Hagman

Just rigid clamping.

Ville Leminen

Okay. Because as you probably know it has quite a big difference, so you might have different results when comparing hydro forming and press forming if you take that into the analysis.

Anton Hagman

What I can say about the clamping was that instead of applying a static force in my simulation, I set it at a static distance. But of course you get less material under the clamp as the material is drawn into the mould.

Ville Leminen

Okay. Thank you.

Torbjörn Wahlström Stora Enso.

I do not find the results of the post forming short tensile tests obvious. For example the wet formed samples had lower stiffness compared to the dry ones. Can you speculate upon the reason for this? Did the density change for example?

Anton Hagman

Maybe. It's a totally different drying route, so they might have a different density. I haven't made comparisons.