Utilization of Production-scale Machine in Experimental Fiber Material Convertibility Testing Using a Novel Press-forming Tool Set

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The convertibility of paperboard in a press-forming process was studied using a novel type of tool set that allows forming of small substrates such as laboratory handsheets (*i.e.* experimental materials) to investigate the role of mold design on substrate-press-tool interaction. The tool set makes it possible to prepare rectangular trays in both sliding and fixed blank modes in a pilot-scale press-forming machine. The tests showed that the fixed-blank mode makes it possible to estimate the elongation of the substrate in the forming process by determining the maximum forming depth for rupture-free samples. A more detailed inspection with an optical microscope of grid-patterned materials revealed that elongation took place mostly on the rim area in addition to the tray wall, and that the outer dimensions of the blank remained practically unchanged. The behavior of the material in press forming process was evaluated in addition to the novel tool set in a bigger, production-scale mold, and results showed good agreement between the small tool set and the standard mold, in spite of the dimensional differences. The smaller size of the mold did not require a compromise in any aspect of the press-forming process.

Keywords: Forming tool; Press-forming; Paperboard; Elongation; Convertibility

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INTRODUCTION

Sustainable paper and paperboard materials are globally the most widely used packaging materials (Rhim 2010). Compared to plastics, the conversion of wood-fiber-based packaging materials into three-dimensional shapes is considered more difficult, which is in many respects a consequence of their more heterogeneous structure – there are local variations in physical properties, but typically a material is evaluated against its overall performance (Hagman and Nygårds 2012). A typical technique for producing packages from paperboard is press-forming (Leminen *et al.* 2013), in which a pre-cut and pre-creased substrate is placed between male and female tools. Typically at least one of the forming tools is heated. In order to maximize the rigidity of the trays, the blank is usually fed into the press so that the longer side of the blank is parallel to the machine direction (MD). Other forming methods for paperboard include deep-drawing (Hauptmann and Majschak 2011) and hydroforming (Groche *et al.* 2012).

The physical properties of a substrate are typically reported based on common laboratory measurements. The tensile properties of fiber-based substrates are affected by their moisture content (Rhim 2010) and the applied drawing speed (Andersson and Sjöberg

1953). However, there is not necessarily a correlation between strength properties and formability, and the presence of a coating layer also affects the formability regardless of the forming method (Lyytikäinen 2015; Leminen *et al.* 2016). The physico-mechanical properties of fiber-based substrates are thus likely to change in a converting environment, not the least due to a higher moisture content that lowers the elastic modulus (Salmén and Back 1980). In fact, it has been claimed that the strain-at-break of paper can increase by 20% if the moisture content of the sample is increased from 6% to 14% (Linvill and Östlund 2014), and this change is related to alterations within the fiber wall and bonds between the fibers due to a variation in the amount of free water (Vishtal and Retulainen 2014). The effect of several process-related parameters such as mold clearance (Leminen *et al.* 2013) and heating arrangement (Tanninen *et al.* 2014a) on the material performance in forming have been studied. The quality of formed trays is affected by the forming velocity, but it seems that the optimal velocity must be determined for each material separately (Leminen *et al.* 2016). The influence of pulp type and of the properties of the fibers and fiber network on the formability are also well known (Hauptmann *et al.* 2015; Vishtal *et al.* 2012). For instance, locally the material is more extensible in the case of dense substrates (Hagman and Nygårds 2012), whereas a combination of a higher beating degree and an enzymatic treatment increases the average strain-at-break value (Fillinger 2016). Surface treatments with natural polymers such as agar, gelatin, and poly-lactic acid have also been reported to increase the extensibility of fiber-based substrates (Vishtal *et al.* 2015; Rhim and Kim 2009).

Rupturing of the blank is a typical defect in deep-drawing (Wallmeier *et al.* 2016), hydroforming (Fillinger 2016), and press-forming (Tanninen *et al.* 2014b) processes. The reasons for the failures in deformation are linked to inadequate physical properties such as strength and elongation in relation to process parameters and tool geometry. The strain behavior of the blank paperboard depends on the length-to-width ratio of the extensibility, and the extensibility of the top layer is often higher than that of the whole sample in a multi-layered board (Hagman and Nygårds 2012). Elongation is an important material property especially in fixed-blank press-forming, since the blank is not allowed to slide during the forming stage and more tensile deformation takes place compared to a sliding blank process (Vishtal 2015). In deep-drawing, the blank-holding force has the greatest influence on the occurrence of rupture, but the forming velocity also has some effect, depending on the degree of z-directional compression during the forming (Wallmeier *et al.* 2016). The stresses to which the paperboard is subjected during the forming process are at least in part linked to the frictional properties of the tools and the substrate (Vishtal and Retulainen 2012), and the stickiness of bio-based coatings onto tools (Leminen *et al.* 2015). The friction of paper-based materials is affected by the surface roughness and surface chemistry, and paper-paper friction increases with increasing moisture content (Fellers *et al.* 1998). However, both kinetic and static paper-metal friction have been reported to decrease with increasing temperature, probably due to lubricative effect of evaporated water from the substrate or redistribution of oleophilic compounds on the surface (Vishtal *et al.* 2014; Back 2001). The glass transition of polymeric additives such as latex binders must be taken into account when the rupturing tendency of a material is discussed, since the accumulation of contaminants alters the friction on the tool surface (Tanninen 2015) and changes in thermal diffusion take place at the substrate-tool interface. All this suggests that material convertability cannot be predicted comprehensively by standard laboratory measurements and it is thus advisable to study the material performance in pilot-scale or production-scale converting machines.

The aim of this study was to create a test setup that combines a novel forming tool set and a pilot-scale press-forming unit. The function of the test setup was verified by comparison with a production setup. The material behaviour in press-forming was evaluated by means of converting test runs, and results obtained with the full-size mold set were compared with results obtained with the scaled-down version. Material elongation behavior during the press-forming phase and the strain distribution on the blank area were given special attention during the experiments.

EXPERIMENTAL

Materials

The blank size for the new mold was chosen so that the development of experimental materials for conversion would be as simple as possible. A commercial paperboard was used in this study, but the easiest way to produce experimental samples is by making laboratory handsheets (165 x 165 mm), from which it must be possible to die-cut a blank. The blank size was set to 140 x 150 mm to allow for a slight shrinkage of the material. The shape of the blank was rectangular instead of square to make possible the easy identification of the fiber orientation in the finished packaging.

The material used in the die-cutting tests and tray pressing was a commercial solid bleached sulphate (hardwood SBS) three-ply polyethylene-terephthalate-(PET)-extrusion-coated paperboard with a substrate grammage of 350 g/m^2 and a coat weight of 40 g/m^2. The material had an alkyl ketene dimer (AKD) hydrophobic sizing. The material was stored in a humidity-controlled chamber at 80% relative humidity to maintain the delivery moisture content of the paperboard. The moisture content was determined before converting tests with an Adams Equipment PMB 53 Moisture Analyzer. The measured moisture content of the material was 8.8%, which was in the range of typical moisture contents before press-forming (Tanninen 2015).

Physical properties of the coated board are given in Table 1. The tensile strength and strain-at-break of the reference material were measured according to ISO 1924-3:2005 in the machine direction (MD) and cross direction (CD). Thickness, density, and bulk were determined in accordance with ISO 534:2011. The thickness of the coating layer was assessed from cross-sectional scanning electron microscope images (Hitachi SU3500 SEM equipped with a SEI-detector; imaging carried out with an acceleration voltage of 15 kV) as shown in Fig. 1. The density profile of the sample was not constant, since the outermost SBS layer at the reverse side was considerably bulkier than the middle layer or the layer located below the PET coating.

Table 1. Physical Properties of the Substrate

Property	Value
Thickness (coated substrate), [µm]	443
Thickness (coating layer), [µm]	45
Density, [kg/m^3]	880
Bulk, [cm^3/g]	1.13
Tensile strength, [kN/m] (MD/CD)	27.3 / 14.3 (RH 50%)
Strain at break, [%] (MD/CD)	1.7 / 4.5 (RH 50%)

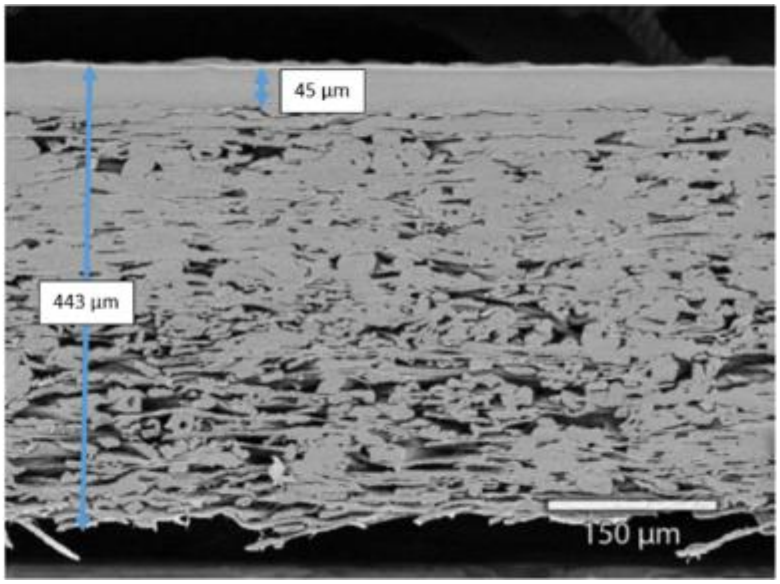

Fig. 1. Cross-sectional SEM image of the substrate. Note the substantially lower density of the uncoated side of the material compared to that of the topmost layer

Press-forming tool set - MiniMould

Experimental materials are typically produced in small quantities, and the use of full-scale press-forming equipment is often impractical or even impossible. There is no need for a completely new testing device if a mold set for smaller samples can be designed and manufactured for production-scale machinery. In this way, applicable features of the forming cycle, such as process control and forming forces, are equivalent to a larger scale setup. A novel press-forming tool set, named MiniMould (Fig. 2), was therefore designed. It consists of four main parts: the male mold (1), the female mold (2), the rim tool (3) and the heating unit (4). The heating unit includes three bar-shaped electric heating elements. The temperature of the molds is monitored with three sensors positioned at locations critical for the press-forming.

Fig. 2. Press-forming tool set

Parts of the tool set were machined from premium grade stainless tool steel (Stavax). The tool material has good wear/corrosion resistance, good machinability, and excellent polishability, all essential properties in the manufacture of press forming molds. After the machining stage, the mold components were hardened and polished to ensure uniform friction between the tool surface and the blank.

The maximum size of the rectangular test tray is 90 x 80 x 35 mm, and the tray depth can be varied between 1 and 35 mm with an accuracy of 0.5 mm. The press-forming tool set can be used in two fundamentally different ways as shown in Fig. 3. In the fixed blank method, a smooth blank (1a) is clamped between the rim tool and the female mold, and sliding of the blank is prevented by a large blank-holding force. The forming of the blank is then based mainly on the elongation of the material, and the forming depth therefore is limited (1b). In the sliding blank method, corners of the blank are creased (2a), and it is possible for the blank to slide. Forming is based on the folding of the blank in addition to stretching of the material, and this makes the forming of deeper trays (2b) possible.

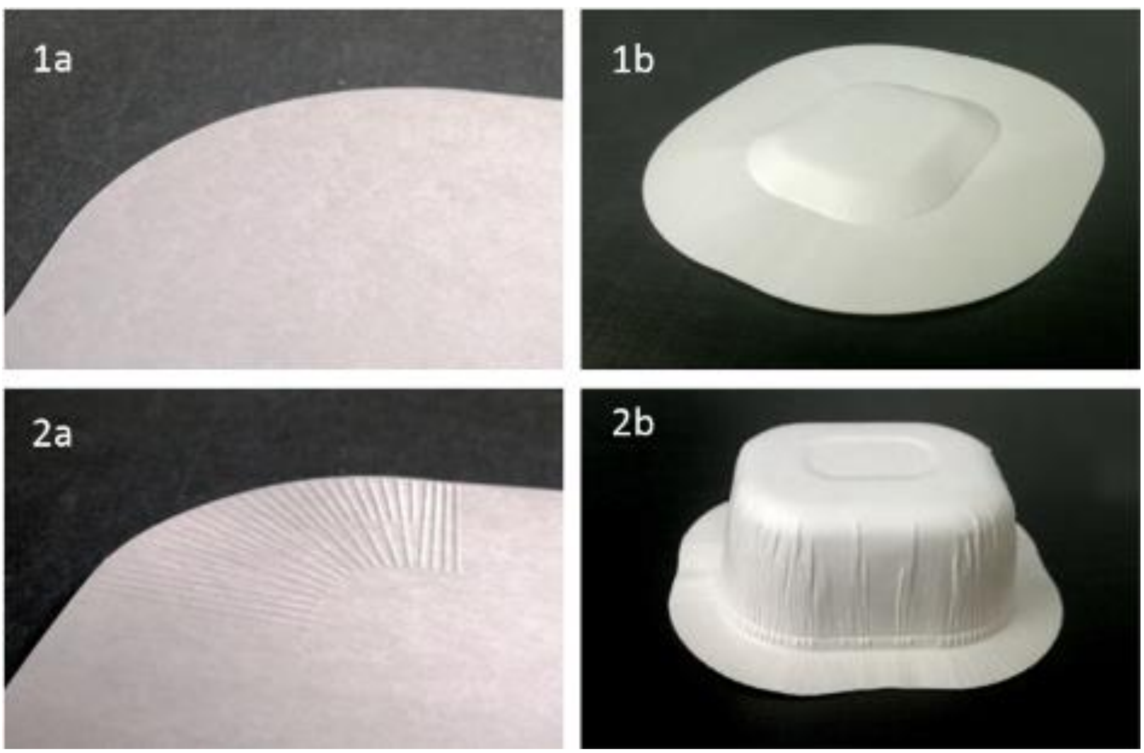

Fig. 3. Methods of press-forming. 1a) a smooth blank for fixed blank press-forming, and 1b) a tray with a depth of 7 mm formed using the fixed blank, 2a) a creased blank for sliding blank press-forming, and 2b) a tray equipped with a bottom indentation and a depth of 35 mm formed using the sliding blank.

Forming tests were also performed with a full-size mold set. Gastronorm (GN) sizes are standard sizes of containers used in the catering industry, specified in the EN 631 standard (SFS-EN 2006). The mold set used in the tests produces GN1/4-standard size (265 x 162 x 38 mm) paperboard trays that are typically used for *e.g.* convenience food packaging. The trays and their related dimensions are presented in Fig. 4. The essential dimensions of the two test trays and their ratios are presented in Table 2.

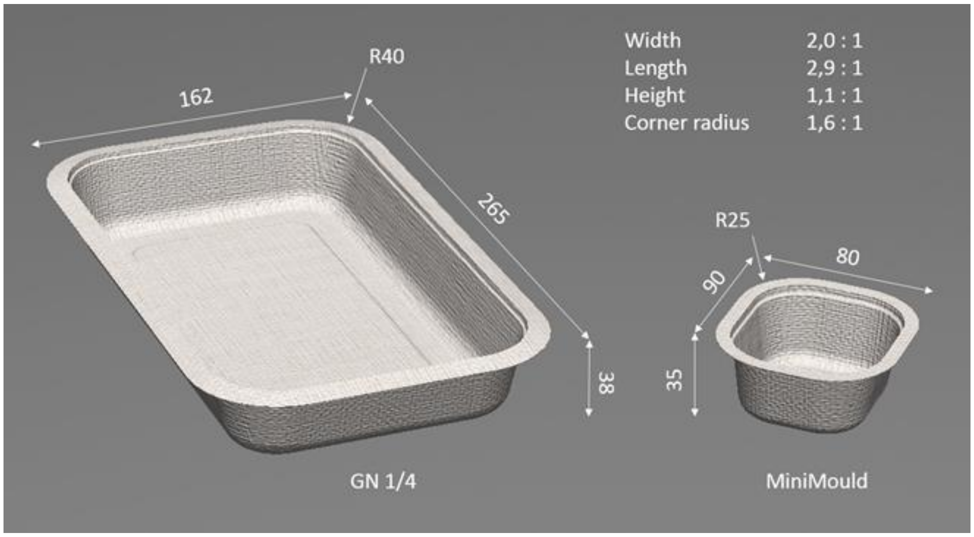

Fig. 4. Trays used in converting tests

Table 2. Comparison of the GN 1/4 and MiniMould Test Trays

	GN ¼	MiniMould	The ratio between GN 1/4 and MiniMould
Width / Blank, [mm]	216.3	140	1.55 : 1
Length / Blank, [mm]	319.3	150	2.13 : 1
Width / Tray, [mm]	162	80	2.03 : 1
Length / Tray, [mm]	265	90	2.94 : 1
Corner radius / Tray, [mm]	40	25	1.60 : 1
Maximum forming depth, [mm]	38	35	1.09 : 1

Determining the Detailed Distribution of Elongation

The distribution of elongation was studied in detail by printing a 4 x 4 mm grid on the uncoated surface of the blank using an inkjet printer suitable for thick substrates (Lomond Evojet Memjet printer with aqueous dye-based CMYK inks). Printed blanks were press-formed and the resulting trays were evaluated with a quality monitoring system, based on a Cognex IS5605-11-smart camera and integrated vision software. Examples of grid-printed samples are presented in Fig. 5.

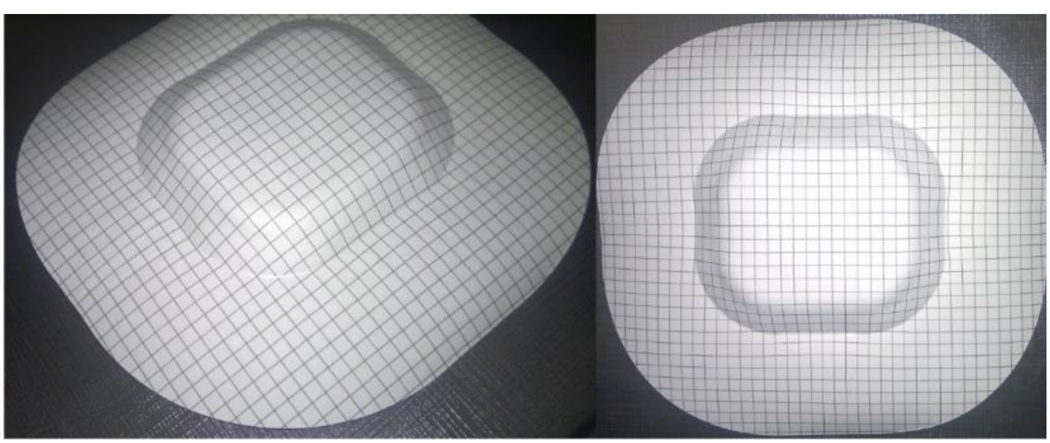

Fig. 5. Grid-patterned tray samples

RESULTS AND DISCUSSION

Distribution of Elongation

Before the forming tests, it was obvious that in fixed-blank press-forming the elongation occurred mainly in the part of the tray blank that was not in contact with the forming tool surfaces, as shown in Fig. 6 with a green arrow. In preliminary tests, the amount of elongation was calculated on the basis of the forming depth and the tool geometry, and it was quickly discovered that the calculated elongation values were much greater than the values obtained in tensile strength tests (Table 1). This indicated that the elongation occurred within a wider section of the blank than expected.

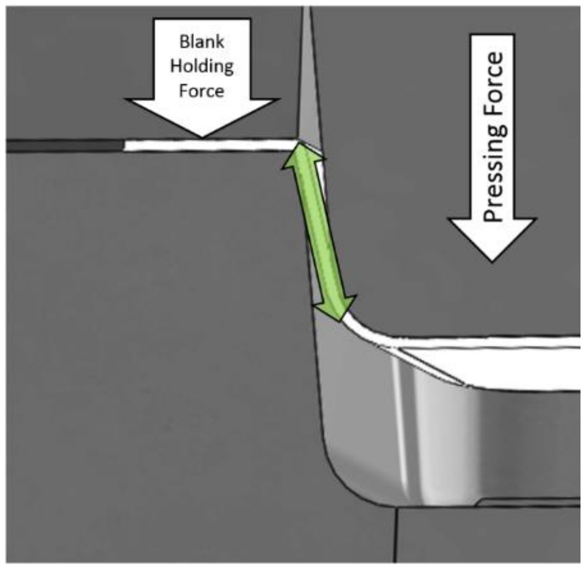

Fig. 6. The part of the blank without direct contact with the forming tools

The distribution of elongation during forming was assessed in detail by using grid-printed blanks in the fixed-blank mode with the assistance of a machine-vision system with a resolution of 2456 x 2048. A single pixel is equivalent to an area of 0.017 x 0.017 mm. Images were taken 650 mm above the tray bottom to prevent image distortion. The vision software recognizes printed line patterns and calculates automatically dimensions between lines. The distribution of elongation could be deduced by analyzing the straightness of the grid lines and their parallelism utilizing a pattern recognition feature of the system. In the sample tray corner area, the minimum detectable strain is 0.12% with used resolution. Changes in the form of lines caused by the press-forming in the cross direction are shown in Fig. 7.

The elongation was calculated as,

$$\frac{A_2}{A_1} = \frac{L_2 * w}{L_1 * w} = \frac{L_2}{L_1} = \frac{7.78\,mm}{7.18\,mm} = 1.083 \quad (1)$$

where A_1 is the area that is not in contact with the substrate before forming, A_2 is the area of the same region after forming, L_1 is the length before forming, L_2 is the length after forming, and w is the width of the substrate.

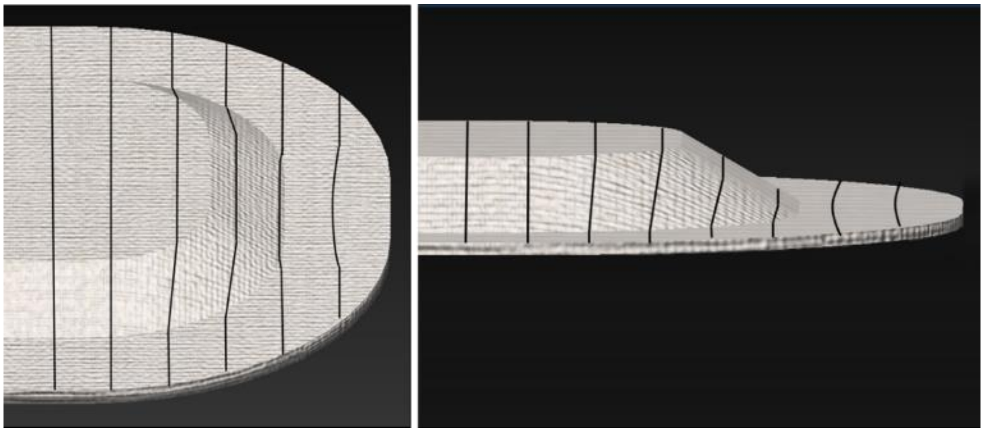

Fig. 7. Press-formed sample with grid lines. Only lines parallel to the cross direction of the paperboard are shown.

If elongation occurred only in the area that is not in contact with a forming tool surface, an elongation of 8.3% would thus be needed in a depth of 3 mm in order to avoid substrate fracture. In a tensile strength test, only 4.5% elongation was measured in the cross direction, which indicates that the elongation must be distributed over a larger area, and a study of the grid-patterned trays revealed that elongation occurred over an area approximately 92% larger than expected. This suggests that an elongation of 8.3% was not required until the forming depth was 9 mm.

It should be noted that the amount of elongation did not increase linearly with increasing forming depth due to mold geometry (see Fig. 4). Elongation during press-forming was distributed into the tray rim and the tray bottom corner (orange arrows) in addition to the tray wall (green arrow), as shown in Fig. 8. In addition to less elongation in the tray wall, the grid-pattern analysis revealed that most of the elongation took place in the rim area where the sample was clamped between the rim tool and the female mold during the forming phase. Outer dimensions (width and length, see Table 2) of the blank remained unchanged during forming with the fixed-blank method.

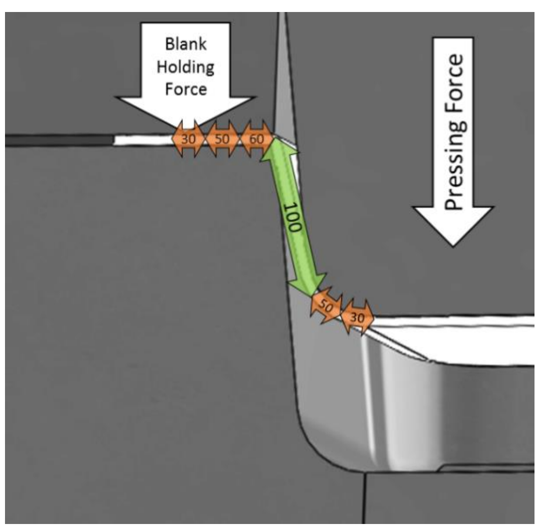

Fig. 8. Elongation of the tray blank during press-forming. Values in arrows indicate comparable level of elongation (100 = maximum elongation).

Estimation of Material Elongation Based on Tray Depth

The elongation was estimated as a function of tray depth on the basis of the grid-pattern analysis and laboratory tensile strength measurements. The approximate elongation during press-forming using the fixed-blank method is presented in Fig. 9. Elongation values were calculated on the basis of the variable angle of substrate transfer, the forming depth, and the distance between the mould folding edges. The maximum forming depth with this substrate in the fixed-blank mode was 7.3 mm (Table 3), which corresponds to an elongation of *ca*. 6%. The press-forming parameters used were: blank-holding force 4.8 kN, female mold temperature 160 °C, male mold temperature 50 °C, pressing force 120 kN, and pressing velocity 150 mm/s.

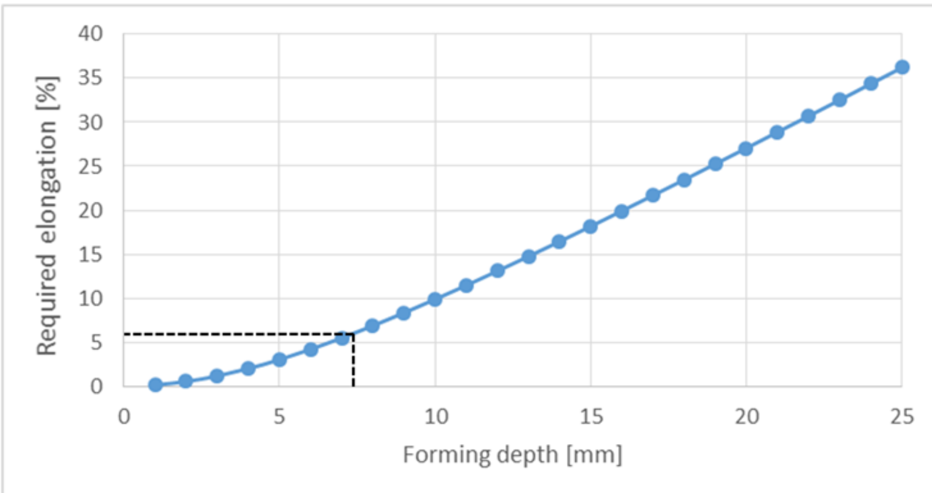

Fig. 9. Required material elongation as a function of forming depth. The dashed line represents the maximum forming depth measured with the fixed-blank mode.

A comparison with the strain-at-break values measured with a tensile tester (MD – 1.7%, CD – 4.5%, see Table 1) revealed that the material elongation in the three-dimensional converting process was substantially higher. The laboratory strain-at-break values were, however, determined according to the ISO 1924-3:2005 standard with a drawing speed of 100 mm/min at RH 50%, and these conditions were not the same as those in the pilot test setup, for which the velocity was higher due to industrial-scale machinery. Linvill and Östlund (2014) have suggested that the strain-at-break value of paper can increase substantially if the moisture content is increased gradually from 6% to 14%. The strain properties of fiber-based substrates under standard conditions (23 °C, 50% RH) differ from those of samples stored at 80% RH for converting. Lyytikäinen (2015) showed that the tensile properties of paperboard are dependent on the drawing speed, but the drawing speed in the laboratory test method is substantially slower than that of a press-forming process. It has been reported that higher forming velocity reduces the probability of rupture occurring in a deep drawing process if the material does not experience z-directional compression during the process (Wallmeier *et al.* 2016). Since the substrate did not reach the bottom of the female tool (7.3 mm < 35 mm), the contact area between the tool and the substrate remained relatively small, and it seems that the finding of Wallmeier *et al.* (2016) are also to some extent valid in press-forming if the fixed-blank mode is used. The strain behavior of paperboard is also affected by the length-to-width ratio of the sample (Hagman and Nygårds 2012). The length-to-width ratio of the test piece in the laboratory test method was 9.4 (141 mm/15 mm), whereas the ratio was only 1.07 (150 mm/140 mm) for the MiniMould blank. This alone suggests that a direct comparison between the two test methods cannot be made, and that the elongation results obtained with a laboratory tester and a forming machine must be examined as two separate entities.

Comparison between the MiniMould and the Production-scale GN 1/4 Tool Set

A number of press-forming experiments were carried out with the GN 1/4 and MiniMould toolsets, and maximum values of the forming depth and blank-holding force were determined to evaluate the material performance with both tool sets and the data were utilized for a further verification of the MiniMould function. Apart from the blank-holding force, the press-forming parameters corresponded the above-mentioned values. The results presented in Table 3 are average values of 10 samples.

Table 3. Results of the Forming Tests in Different Molds

	GN ¼	MiniMould	The ratio of GN ¼ to MiniMould
Maximum forming depth – Fixed and creased blank	13 mm	10 mm	1.30 : 1
Maximum forming depth – Fixed and smooth blank	10 mm	7.3 mm	1.36 : 1
Maximum blank holding force – Sliding and smooth blank / 8mm depth	96 N	81.6 N	1.17 : 1
Maximum blank holding force – Sliding and creased blank / 8mm depth	148.8 N	103.9 N	1.43 : 1
Maximum blank holding force – Sliding and smooth blank / maximum depth	93.6 N	79.2 N	1.15 : 1

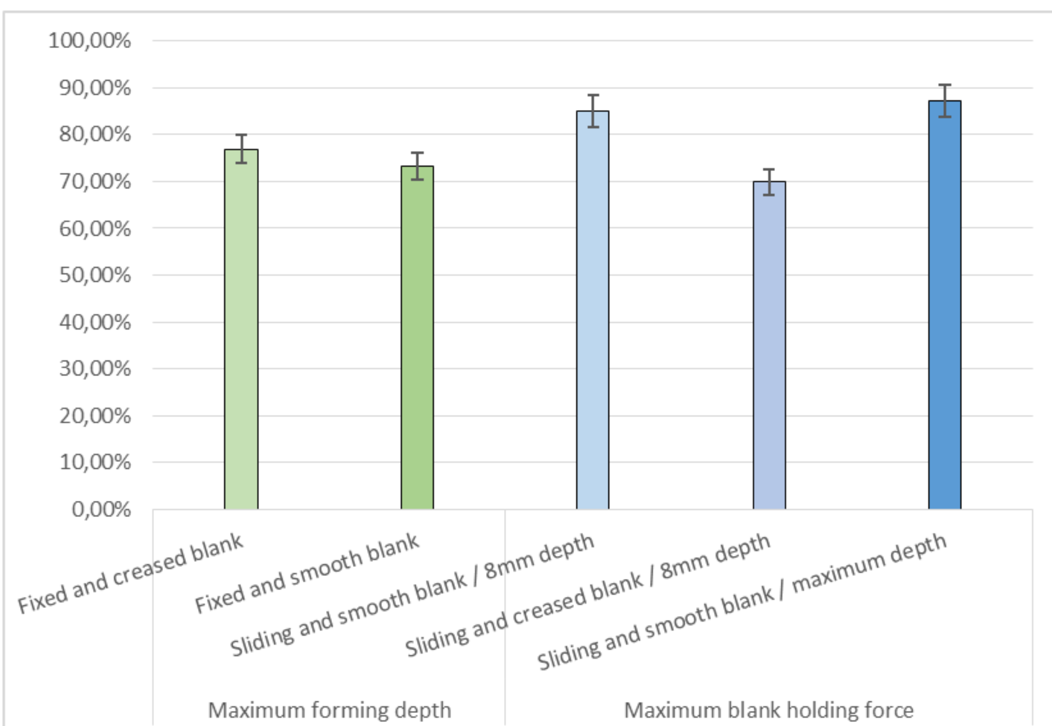

Fig. 10. Forming test results obtained with the MiniMould as a percentage of the GN ¼ results

The results showed that values obtained with the MiniMould were 70 to 87% of the GN 1/4 values, as can be seen in Fig. 10. As expected, using creased samples in the sliding-blank mode made it possible to increase the blank-holding force with both molds, although the relative increase was greater with the GN 1/4 mold. With the fixed-blank mode, the ratio between the molds remained almost unchanged regardless of whether or not the blank was creased, but it became evident that the use of creased blanks made it possible to form deeper trays. Bearing in mind that the novel small mold set was not directly a scaled-down version of the larger one, the results agreed reasonably well with regard to the mold depth difference. When compared to the corner radius difference, the result values were alike but uniformly larger. The tray length and width were of minor importance because the geometry of the tray corner was similar in both the molds; only the wall lengths between the corners had been shortened.

CONCLUSIONS

1. This study describes a way of studying the convertability of small, experimental fiber-based substrates using production-scale machinery. The novel press-forming tool set (MiniMould) makes it possible to evaluate the maximal forming depth and the elongation of the material. More accurate information about the distribution of elongation can be obtained by imaging the produced trays with a machine-vision-based quality management system.
2. Operation of the developed tool set was verified and its integration into the production scale press was found to be satisfactory. The same test setup is suitable for both fixed-blank and sliding-blank press-forming. The press-forming process with the new tool set corresponds well to a production-scale process. The difference in mold depth indicates the attainable values of the maximum blank-holding force and the maximum forming depth. The smaller size of the mold did not make it necessary to compromise in any aspect of the press-forming process.
3. The distribution of elongation can be observed in more detail by printing a grid on the surface of the blank using a desktop inkjet printer suitable for thick substrates. The distribution of the elongation can be deduced by analyzing the straightness and parallelism of the grid lines. In fixed-blank press-forming, the elongation of the blank was divided between the tray rim, the tray bottom corner, and the tray wall. The amount of elongation can be approximated by the forming depth. This makes it possible to evaluate the sample material formability. Elongation took place mostly in the rim region in addition to the tray wall, while the outer dimensions of the blank remained unchanged in forming with the fixed-blank method.
4. The small dimensions of the novel tool set also make it possible to evaluate the formability of classic square laboratory handsheets if the forming is carried out as a sheet-fed process. It can thus be stated that the concept may also provide feedback to early-stage material developers. This study, however, leaves a topic for future studying of the effects of different paperboard layer structures and coatings on material formability with the novel tool set.

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