Measurement of changes in torsional stiffness of press-formed paperboard packages induced by heat load utilizing a developed measuring device

Panu Tanninen | Ville Leminen | Sami Matthews | Arvo Niini | Juha Varis

Mechanical Engineering, Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland

Correspondence
Panu Tanninen, Mechanical Engineering, Lappeenranta-Lahti University of Technology, Yliopistonkatu 34, 53850, Lappeenranta, Finland.
Email: panu.tanninen@lut.fi

Abstract
The press-forming process and the effects of parameter variation on the forming process have attracted great interest lately. The dimensional accuracy of the formed trays and the rigidity and stability of the packages are crucial factors for functionality in packaging lines, especially in fast operating machinery. The torsional stiffness of trays must be at a sufficient level to ensure the functionality in subsequent processes and logistics. The objective of this study was to develop and build a device for measuring the torsional stiffness of whole tray packages, to verify its functionality and to investigate the effect of heat load transferred to paperboard material on the torsional stiffness of the formed trays. The operation of the novel torsional stiffness tester was confirmed, and the tester was found to be suitable for measuring the thermal response of the sample materials and the effect of the fibre direction. Thus, the analysed material does not need to have a homogeneous stiffness property since the differences are noticeable in the measurement results. In addition, the results indicate that tray blanks should be die cut in the machine direction of the paperboard. The torsional stiffness of the tray packages increases, and the outer dimensions decrease as a function of the heat input. The first feature is desirable for packaging functionality and the second feature can be compensated by competent packaging design. To conclude, the use of higher mould temperatures is recommendable if the integrity of the package material is not compromised.

KEYWORDS
heat response, measurement device, paperboard package, press forming, torsional stiffness

1 | INTRODUCTION

Press forming is a manufacturing process used in production of three-dimensional containers from paperboard. It offers a renewable alternative for oil-based plastics in applications such as trays and plates for food packaging. Many food packaging applications utilize composite materials, such as paperboard coated with a plastic layer or other materials. This work continues the work of the authors in the three-dimensional forming of the paperboard. The press-forming process typically utilizes precut and precreased paperboard blanks, which are subsequently formed into three-dimensional objects. The role of tool design for the operation of the forming process is essential. In the challenging converting of fibre-based materials, heated tools can be used to improve the formability of the materials. Previously, the effect

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of heating was investigated, and it was concluded that uniform heating is in a great role in success of forming of the paperboard tray. The forming is done on a precreased blank that is drawn into shape with a mould set consisting of a male mould, a female mould, and a blank holder. Regarding to this method, Leminen et al. found that blank holding force has a direct relation to tray corner formation and resulting gas tightness—a good indicator that the package is successfully formed. Increased blank holding force decreased the oxygen leakage and led to considerably improved shelf life. Hauptmann et al. continued this work investigating the effect of blank holding force curves in the wrinkling of the tray corners. They found that wrong force distribution leads to increased and excessive rupturing in final products.

Groche et al. researched the differences between sheet metal and paperboard forming. They found that the material behaviour and tribological conditions are closely linked to moisture content and temperature in paperboard forming. This highlights the important role of material conditioning in paperboard forming. The heat input affects factors such as the external dimensions of the press-formed trays, and a higher heat input is recommended for better dimensional accuracy. Temperature and moisture are known to influence the elongation behaviour of the fibre-material and the stress relaxation rate, as they increase the plastic deformation.

In addition to the dimensional accuracy of the formed trays, the rigidity and stability of the packages are crucial factors regarding functionality in packaging lines, especially in fast operating machinery. The torsional stiffness of trays has to be at a sufficient level to ensure functionality in subsequent processes and logistics.

There is no existing standard for measuring change in the torsional stiffness of manufactured paperboard packages, such as trays. In comparison with the typically used Chalmers DST stiffness tester that uses 25-mm-wide board samples, the aim here is to enable the testing of whole packages. This leads to conditions in which the measured sample is large, while the required torque is low, requiring a novel approach.

However, there are no previous studies—nor measuring equipment—to investigate the torsional stiffness of converted tray-type or anallogical packages, measure it or improve it. Hence, the objective of this study was to develop and build a device for measuring the torsional stiffness of tray packages, to verify its functionality and to investigate the effect of heat load transferred to paperboard material on the torsional stiffness of the formed trays. To achieve these goals, a series of converting experiments and measurements were performed with the novel device.

2 | MATERIALS AND METHODS

2.1 | Materials

A commercial three-ply paperboard with a substrate grammage of 350 g/m² was selected as the test material for the press-forming experiments. The baseboard consisted of two solid bleached sulfate (SBS) layers with a chemi-thermochemical pulp (CTMP) layer between them. One of the test materials was uncoated, and the other extrusion coated with polyethylene terephthalate (PET), which had a coat weight of 40 g/m². The material had an alkyl ketene dimer (AKD) hydrophobic sizing. The tensile strength was measured using an L & W Tensile Tester (ABB, Stockholm, Sweden). The tensile strengths were 27.39 kN/m in the machine direction and 14.35 kN/m in the cross direction. The fibre dimensions of the paperboard were measured using an L & W Fiber Tester (ABB, Stockholm, Sweden). The fibre length, fibre width, and kink index were measured at 1.1 mm, 22.5 μm, and 1.13, respectively. The thickness of the uncoated material was measured at 465 μm and the coated material at 480 μm with a Messmer Büchel model 49-56 digital micrometer. The materials were stored in a humidity-controlled chamber at 80% relative humidity to maintain the delivery moisture content of the paperboard. The moisture content was verified before converting tests from the base material with an Adams Equipment PMB 53 Moisture Analyzer. The measured moisture content of both materials was approx. 8.1%, which was considered suitable moisture content for press-forming process.

The moisture value of the coated sample only represents the proportion of base board, as the PET-coating was not found to absorb moisture due to its barrier properties.

2.2 | Press forming of paperboard trays

Sample packages were produced in a series of converting phases at Lappeenranta-Lahti University of Technology’s (LUT) Laboratory of Packaging Technology. The production of the press-formed trays included die cutting of the tray blanks and press forming of the trays. A GN ¾ tray, samples presented in Figure 1, was selected for converting trials because it is relatively demanding to form, resulting in differing results between studied materials. The tray dimensions are 265 mm × 162 mm × 38 mm.

Tray blanks were prepared with the flatbed-die cutting module of the LUT Packaging Line. The die cutting force was adjusted according to the properties of the reference baseboard (Trayforma 350). The force used was equivalent to the normal production run. The tray blanks were die cut the long side of the tray either in the machine
direction (MD) or in the cross direction (CD) of the paperboard to determine the effect of the fibre direction on the stiffness of the tray package.

The trays were press formed with the forming module of the LUT Packaging Line, and the following process parameters (optimised for production run) were used: male mould temperature 50°C, pressing speed 120 mm/s, blank holding force 1.3 kN, and pressing force 150 kN. The magnitude of thermal load transferred to the material during the forming was controlled by two process parameters: female mould temperature and dwell time. Three different female mould temperatures (60°C, 120°C, and 180°C) were applied. The highest temperature was selected according to the melting temperature of the polymer, and the others were evenly distributed values. Three different dwell times (400 ms, 1000 ms, and 1600 ms) were used in the experiments. The dwell time values were evenly distributed according to a feasible range of the standard industry dwell times. The influence of forming parameters and conditions such as moisture and temperature in press forming was established by Östlund et al. and a more thorough description of the press-forming process can be found in paper by Laukala et al.

### 2.3 Tray rigidity analysis

Based on the Chalmers Dynamic Tester apparatus and the ASTM D1043-16, a novel torsional rigidity testing device was developed. Figure 2 illustrates the device, which enables various testing procedures such as evaluating the package rigidity in relation to factors including material properties and manufacturing process parameters. This enables source reduction by means of material thickness and weight optimisation, utilising package geometry and manufacturing process optimisation. In this study, the torsional rigidity of press-formed paperboard trays was measured as a function of the forming tool temperature.

The device was designed and manufactured at LUT for more accurate analysis of package functionality. The device consists of adjustable holding clamps with interchangeable clamping heads and an adjustable distance for varying packaging dimensions. The device consists of two ends, which have concentrically aligned axles, which determine the centre of rotation. The axes are connected to clamps. One end of the device is fixed (marked with A in Figure 2) and contains an angular measurement system (Cline Labs Inc. Electronicclinometer type R1 with range of ±60° and resolution of 0.1°, marked with B) and a scale-like 600-mm high precision bar (C) for changeable weights to create torsional force that bends the clamped package. Changeable package-specific brackets are attached to the clamps. The experiments employed brackets with a width of 10 mm and a length of 80 or 150 mm, depending on which side the tray was clamped. The other end of the device is floating (D), which enables unconstrained uniaxial movement. This facilitates dimensional changes in the clamped package (E), which can be measured accurately utilising the angular sensor. The axle on the floating end can be attached with a pre-tensioning by rotating the starting position from the horizontal position. The experiments for this study were performed without pre-tensioning.

Two different clamping methods were used:

- Tray clamped on the short side
  - Measurement with weights of 60 g (0.018 Nm) and 120 g (0.036 Nm)
- Tray clamped on the long side
  - Measurement with weights of 120 g (0.036 Nm) and 240 g (0.072 Nm)

Combinations of two clamping methods and two die cutting directions resulted in the four measurement modes presented in Figure 3.

A bigger mass had to be used when the tray was clamped on the longer side, because the torsional angles caused by the 60-g weight was unobservable to the angle sensor. The measurement was made first clockwise and then counter-clockwise from the same sample. The reported value is an average of six samples.

Paperboard is a viscoelastic material, and its properties include time-dependent creep. This was taken into account in the measurements by allowing the tray to be under load for 60 s before recording the result. After this time period, the deformation was found to be minor in the preliminary experiments. In addition, the use of a longer period would not be justified considering the end use of the tray package (how long the tray is handled after removing the film lid).

All tray samples were measured before the torsion rigidity test with a quality monitoring system consisting of a smart camera and a backlit table.

Based on the axis of rotation and geometry of the tray, the theoretical area moment of inertia \( I \) was calculated as follows in SolidWorks 2019:

\[
I_{\text{short side}} = 188.1 \text{kgm}^2
\]

\[
I_{\text{long side}} = 253.2 \text{kgm}^2
\]

The torsion constant (\( J \))—an important determinant in torsion—is approximately the moment of inertia. Therefore, the mentioned
moment of inertia values are used in the evaluation of torsional rigidity. For simplicity, the effect of profile warping was not investigated in detail, as the maximum rotational angle is less than 30° based on preliminary experiments.

3 | RESULTS AND DISCUSSION

In preliminary tests, it was immediately evident that when the test tray is fastened on its short side and the rotation occurs around the axis of the long side, the tray can buckle under significantly less torsional load. If both clamping methods used the same test weights, the results were clear only with one method. Therefore, the decision was made to use clamping method specific test weights. A different combination of tray geometry and material may also allow the same weights to be used. The accuracy of the device and the reproducibility of the results were also verified by testing different tray samples in the preliminary tests. In the case of paperboard trays, the same sample could not be used twice due to permanent deformation. However, the repeatability of a batch, picked from large-scale production run, of 30 sample trays press formed with constant and optimized parameters was ±0.37° with 60-g weight. Samples made entirely of plastic could be tested several times and the repeatability was found to be at the same level as the accuracy of the angular measurement system. Figure 4 shows an example of the tray package being tested.

When a 60-g test weight was used to measure the stiffness of the tray package, it was observed that the rotational stiffness of the trays increased as a function of heat input. In the samples with the longest dwell time, there was a slight dip at the highest temperatures, but otherwise, the results were consistent. The effect of the fibre orientation on the stiffness of the tray package was clear: the samples die cut in the MD had greater torsional rigidity, as Figure 5 displays.

With a heavier test weight of 120 g, the results differed more, indicating that the tray package was closer to the point of buckling. When the tray blank was die cut in the CD, the stiffness of the tray increased with heat input. In contrast, the results show that the stiffest MD-cut sample trays were produced at a 120°C mould temperature, as Figure 6 presents.

Results similar to those obtained with tray packages made of baseboard (Trayforma 350) were also obtained with polymer coated samples (Trayforma 350 + PET40), as Figure 7 shows. In PET-coated samples, the increase in tray stiffness as a function of heat input was even greater, which can be assumed to be due to the sealing of the polymer layer at the corners of the package.

In tests with a larger weight of 120 g, the increase in tray stiffness was substantial only with CD-cut specimens, which can be seen in Figure 8. Variable changes in stiffness, as with samples made of baseboard, were not observed in MD-cut sample trays. The stiffness did not increase significantly when the mould temperature rose above 120°C.

The method of cutting the blank relative to the fibre direction of the paperboard had a clear effect, as Figures 6 and 8 demonstrate, when the blank was rotated with short side clamping. However, when the clamping was on the long side, the results were consistent, and the heat input steadily increased the rigidity of the tray packages. Regardless of the die cutting direction, the highest tray stiffness was achieved by a combination of the highest mould temperature and the longest dwell time, which is evident in Figures 9 and 10.

The same observation was made on measurement results presented in Figure 11; heat import was found to increase the stiffness of the tray packages in PET-coated samples. Surprisingly, the results obtained from MD-cut specimens at mid-range mould temperatures included a deviation with shorter dwell times. Phenomenon was assumed to be related to partial bonding of polymer coating at the adjacent creases in tray corners.
Results obtained with different testing weights differed less in PET-coated samples than in uncoated ones. Graphs in Figure 12 have the same unexpected shapes at mid-range mould temperatures, but at higher temperatures, differences in the results are equalised.

With a larger test weight of 240 g, the rotation angles increased, and the significance of the fibre orientation was more evident in the results. The CD-cut sample trays were discovered to be more rigid, which is noticeable in Figures 10 and 12. The finding is the opposite to the results obtained with short side clamping measurements (Figure 8).

The results in Figures 13 and 14 show that the increase in heat input consistently reduces the outer dimensions of the tray package.

The change in the outer dimensions of the tray packaging made of polymer coated Trayforma 350 + PET40 material was similar to the outer dimensions decreasing as a function of heat input.

4 | DISCUSSION

The proposed testing method is a developed version of the well-established ASTM D1043-16 “Standard Test Method for Stiffness Properties of Plastics as a Function of Temperature by Means of a Torsion Test.” The main difference between polymers and paperboard is that paperboard has anisotropic nature. This difference in material
behaviour was successfully noted when the proposed measurement system was designed by allowing unconstrained movement in the direction of the rotation axis.

Based on the results of this experimental study, it is clear that the measured torsional angle on a constant load has a direct correlation with the total torsional stiffness of paperboard tray packages. It is also clear that the orientation of the tray and resulting moment of inertia are in a strong role in determining the torsional rigidity. The pre-calculated torsional moment of inertia constants were 34% higher on the long side (l_long side); this effect can also be clearly seen in the actual torsional stiffness measurements. The anisotropic nature of the material and the direction of the fibres seem to have smaller yet important effect in the overall torsion strength than the orientation of the geometry. Torsional stiffness is principally governed by rotational bending stiffness which for a plate is proportional to the geometric mean of the MD and CD moduli of the paperboard. Treatments that maintain or possible increase the moduli in press forming such as increased heat and moisture should also result in a higher torsional stiffness.

Typically, the increased temperature led to significantly better rigidity. However, in some cases with polymer coated samples, the intermediate temperature of 120°C resulted in lower rigidity than
the starting temperature of 60°C. This could be caused by incomplete bonding of the coating layer in the tray corners at lower temperatures. Therefore, a higher forming temperature of 180°C is recommended in all cases.

The effect of dwell time was found to be minor. A similar observation was made in a previous work by Tanninen et al.7 In most cases, a longer dwell time increased the stiffness of the tray packages, but the significance was small compared with the effect of the mould temperature.

The torsional stiffness of the polymer coated material was significantly higher compared with the uncoated material. The extrusion coating polymer increased the overall paperboard thickness from 465 μm to 480 μm, which can be expected to improve the stiffness of the material to some extent.

The results are in line with the earlier analogical studies by Vishtal et al.,15 where the rigidity was found to be based on the orientation of the package and used temperatures. Similar behaviour was also reported by Hauptmann et al.,16 who verified the result with a statistical regression model. Wallmeier et al.17 found that the blank holding force is directly related to the wrinkling of the final paperboard product and also concluded the effect of fibre orientation.
A previous study revealed that all heat related parameters, that is, mould temperatures, dwell time, and pressing speed, can be used to adjust the outer dimensions of the paperboard tray. Based on these results, it was assumed that the process parameters used as variables in the torsion rigidity tests cause changes in tray dimensions. The research results confirmed the preconception.

Angular measurement is an easy way to determine the torsional stiffness and rigidity of paperboard packages, and the method introduced in this study can be easily used with other materials and geometries. Based on the results obtained by these methods and this experimental setup, it is possible to calculate a universally comparable value for the shear modulus (G) for paperboard trays.

This study provides thorough experimental results and forms a basis for numerical evaluation with the finite element method, which could be investigated in the future research. It would also be interesting to optimise existing packaging geometries based on torsional rigidity, which could lead to significant source-reductions. In addition, measurements in varied humidities and temperatures are of interest, as the device can be inserted into a climate cabinet to simulate changes in the atmosphere.
CONCLUSIONS

The operation of the novel torsional stiffness tester was confirmed, and the tester was found to be suitable for measuring the thermal response of the sample materials and the effect of the fibre direction. Thus, the analysed material does not need to have homogeneous stiffness properties, since the differences are noticeable in the measurement results.

Sample trays die cut long side in the machine direction (MD) were significantly stiffer with all press-forming process parameters when measurements were performed with clamping on the short side. When the clamping was on the long side of the sample tray, samples die cut in the cross direction (CD) of the paperboard were slightly stiffer at lower mould temperatures, but at higher temperatures typically used in production runs, the differences in results were minimal. Based on these results, die cutting of the tray blanks should be performed in the machine direction of the paperboard parallel to long side of the tray. This choice enables maximum tray stiffness to be achievable and more reliable operation of the package in end use.

The torsional stiffness of the tray packages increases, and the outer dimensions decrease as a function of heat input. The first
feature is desirable for packaging functionality, and the second feature can be compensated by competent packaging design. To conclude, the use of higher mould temperatures is recommendable, provided that the integrity of the package material is not compromised.

ACKNOWLEDGEMENT
The authors would like to thank Stora Enso for providing sample materials.

DATA AVAILABILITY STATEMENT
Data available on request from the authors.

ORCID
Panu Tanninen https://orcid.org/0000-0001-6570-5253
Ville Leminen https://orcid.org/0000-0001-5854-3321
Arvo Niini https://orcid.org/0000-0002-7728-8140

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How to cite this article: Tanninen P, Leminen V, Matthews S, Niini A, Varis J. Measurement of changes in torsional stiffness of press-formed paperboard packages induced by heat load utilizing a developed measuring device. Packag Technol Sci. 2021;34(10):641-650. https://doi.org/10.1002/pts.2601