Effect of Material Properties on the Paper Cup Manufacturing Process

Juho Bonifer,* Panu Tanninen, and Ville Leminen

The disposable cup market has long relied on paperboard with a fossil-based polymer coating as a replacement for 100% plastic cups. Paperboards with biobased or biodegradable polymer coatings are aimed at reducing the fossil resource consumption of the packaging sector. However, as their properties are inherently different from traditional, fossil-based materials, they can face runnability issues. In order to establish a connection between certain material properties and runnability issues, four coated paperboard materials with differing surface and strength properties were converted into 250 mL/8 oz disposable drinking cups. The materials included two single-side extrusion-coated paperboards and two two-sided dispersion-coated paperboards. The cups were manufactured in two separate runs with minor machine adjustments to affect the resulting cup geometry. A comparison of the manufactured cups and material properties revealed the materials' coefficient of friction to be the major cause of runnability issues or defects. Other suspected properties affecting the performance of cup materials included bending stiffness and compression strength.

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INTRODUCTION

Disposable, fiber-based paperboard cups are an everyday sight for most people due to the prevalence of takeaway culture in the modern world. They are seen as a sustainable alternative to disposable plastic cups, but they still contribute significantly to environmental pollution due to their traditionally polyolefin-based barrier coatings (Schoukens *et al*. 2014; Rastogi and Samyn 2015). Polyolefins such as low-density polyethylene (LDPE) are popular coating materials due to their excellent barrier properties, processability, heat sealability, and affordable price. The strong adhesion between the coating and paperboard makes it difficult or impossible to recycle in traditional recycling mills, causing most disposable cups to end up in landfills or to be incinerated for energy (van der Harst and Potting 2013; Mitchell *et al*. 2014; Yuhui 2018). The yearly consumption of disposable food and drinking cups has been estimated to be around 300 billion cups (Potting and van der Harst 2015). It will most likely continue to grow as the standard of living increases internationally.

Typical materials used for disposable paper cups include extrusion-coated and dispersion-coated paperboard consisting of layered chemical pulp and chemi-thermomechanical pulp called cup board or cupstock, produced from high quality, virgin pulp as per the requirements of food packaging applications (van der Harst *et al.* 2014). The grammage of cupstock varies from under 200 g/m^2 to over 300 g/m^2 and typically has a barrier coating weight of 8 to 20 g/m^2 (Kuusipalo 2008). In most food and drink applications, a barrier coating is required, as paperboard is a porous material with poor barrier properties against liquids and lipids (Rhim and Kim 2014; Schoukens *et al.* 2014). An uncoated cup could absorb its contents or parts of it, causing concerns over food safety as well as usability. In addition to providing a barrier, the barrier coating is responsible for creating the liquid-tight seals on the side and bottom of the cup, as no additional adhesives are used. Simply put, the polymer coating for hot beverage cups needs to display good thermal stability, good liquid barrier properties, and adequate oil barrier properties due to the lipid content of coffee, as well as good heat sealability. The most common barrier coating has been a lining of extruded low-density polyethylene (LDPE) applied onto one or both sides of the base board, depending on the intended application. (Kuusipalo 2008). Hot beverage cups used to serve coffee or tea typically have a barrier coating on the inside, while the outside is uncoated or pigment-coated for printing (Paltakari 2009). Cold drink cups for soft drinks, *etc.*, require an additional, usually lighter barrier coating on the outside due to condensation of atmospheric moisture caused by the cold contents, which, if absorbed by the cup, could compromise its integrity.

Due to legislation and directives aimed at reducing or banning the use of single-use plastic items, bioplastic products, as well as bio-based and recyclable coating polymers for paper and paperboard, are being researched and brought to the market as a replacement. The single-use plastic directive by the European Union placed a ban on 100% plastic cups, among other single-use plastic items, with readily available, sustainable alternatives (European Union 2019). Plastic waste is becoming increasingly problematic despite regulations and the use of recyclable and biodegradable materials. In addition to barrier-coated, converted paperboard cups, other potential environmentally friendly alternatives include composite cups from agricultural waste (Buxoo and Jeetah 2020) and cups molded from pulp. A major limiter in these types of cups is their production speed compared to traditional converted ones, as well as the water consumption of the molded pulp cups. As is the case with converted cups, barrier polymers or waxes need to be used to avoid penetration of liquids into the porous material, hampering their recyclability and biodegradability.

Disposable paper cups are manufactured in a high-speed process ranging from 50 to over 300 cups per minute (CPM), depending on the automatization level of the machine as well as the machine’s construction. “High-speed” is used to refer to the production speed of individual cups as well as the velocity at which blanks move during production. According to high-speed camera footage of a machine with a production speed of 140 CPM, the sliding speed of the blanks was determined to be about 1 m/s while in motion. For reference, the standard ISO 8295:1995, which is used for the determination of the friction coefficient of plastic sheeting uses a speed of 100 or 500 mm/min (0,0017 and 0,0083 m/s, respectively). Automatic machines can be roughly categorized into two groups: the first type has a separate tapered mold (mandrel) for forming the cup wall, which is then transferred to a revolver of male molds for bottom forming. These machines can have the option of ultrasonic sealing for the side seam in addition to hot air and can reach production speeds of up to 180 CPM. The second, faster group of machines forms the cup wall directly onto the molds of the bottom forming revolver, uses solely hot air sealing, and can reach production speeds of up to 330 CPM (Paper Machinery Corporation). As the sealing time of the faster machines is relatively short, only 0.1 to 0.2 seconds due to the high production speed, blank holder clamps are added onto the molds of the bottom forming revolver to keep the seam area under pressure to prevent spring back from affecting the seal on the seam area before cooling.

Cupstock should have robust material properties for both the coating layer and the baseboard due to the demanding nature of the manufacturing process. Coefficient of friction (COF), tensile strength, compression strength, and bending stiffness are all critical material properties to be aware of when evaluating the potential performance and runnability of a cup material. Due to the aligned fiber structure of paperboard, its mechanical properties differ depending on the orientation when measured: machine direction (MD) or cross-direction (CD). For cup blanks, the machine direction of the paperboard is aligned with the short side of the blanks, as bending stiffness is lower in the cross-direction, facilitating the folding of the cup walls. Moisture content also has a notable effect on the strength properties of materials (Rhim 2010; Marin *et al.* 2019), which makes storage conditions of the materials exceedingly crucial due to their tendency to absorb and exude moisture. The criticality of material properties and their relationship with the machine elements and process parameters still needs to be established in the literature.

Furthermore, novel, sustainable materials can come with runnability issues from the cup manufacturers' point of view, caused by different material properties compared to the commonly used LDPE-coated paperboard. Biobased polymers generally have low thermal stability and glass transition temperature (Nguyen *et al.* 2018), and formed coatings may feature brittle or pinhole-prone coating layers, such as in the case of poly(lactic acid)-based barriers and dispersion barrier coatings, respectively (Tyagi *et al.* 2021). Research concerning cups is typically focused on material development with some cup manufacturing (Helanto *et al.* 2022) or on life-cycle analysis (Häkkinen and Vares 2010; van der Harst and Potting 2013; van der Harst *et al.* 2013; Woods and Bashir 2014; Foteinis 2020).

The cup manufacturing process involves converting coated paperboard in the form of wall blanks and a bottom stock reel into ready-to-use cups in a high-speed multi-stage process. The nature of the process causes any converting defects to carry over to subsequent stages. The stages of the converting process are as follows, with those stages causing thermal or mechanical stresses on the materials pictured in Figs. 1 to 4:

1. The blank is removed from a magazine, typically *via* suction cups and transferred to the side seam heaters *via* suction cups or push fingers along the blank track.
2. The sealing areas of the side wall blanks are heated *via* hot air, which can be replaced or combined with ultrasonic sealing.
3. A) The heated blank is transferred to a tapered cylinder (mandrel) and folded over it, after which the heated sealing surfaces are pressed together by a metal bar or the ultrasonic sonotrode to form the side seam and final shape of the cup wall. Faster machines (> 200 CPM) omit the separate mandrel and instead form the side seam on the molds of the following stage (4).

   B) A circular tool punches the bottom blank from the bottom reel and inserts it into the bottom of cup-shaped male molds in preparation for the transfer of the cup wall.
4. The formed wall is transferred onto tapered molds, which already hold the bottom blanks. The bottom portion of the cup wall and the inserted bottom blank are heated by hot air, typically in 2 to 3 stages in preparation for bottom forming. Faster machines feature blank holders on each mold to ensure proper bonding of the side seam.

5. The bottom of the cup wall is pressed against a concave forming tool (curling tool), causing the heated bottom portion of the cup wall to encompass the edges of the bottom blank in preparation for bottom sealing (knurling). The molds can include a tool to keep the bottom blank in place during curling and knurling.

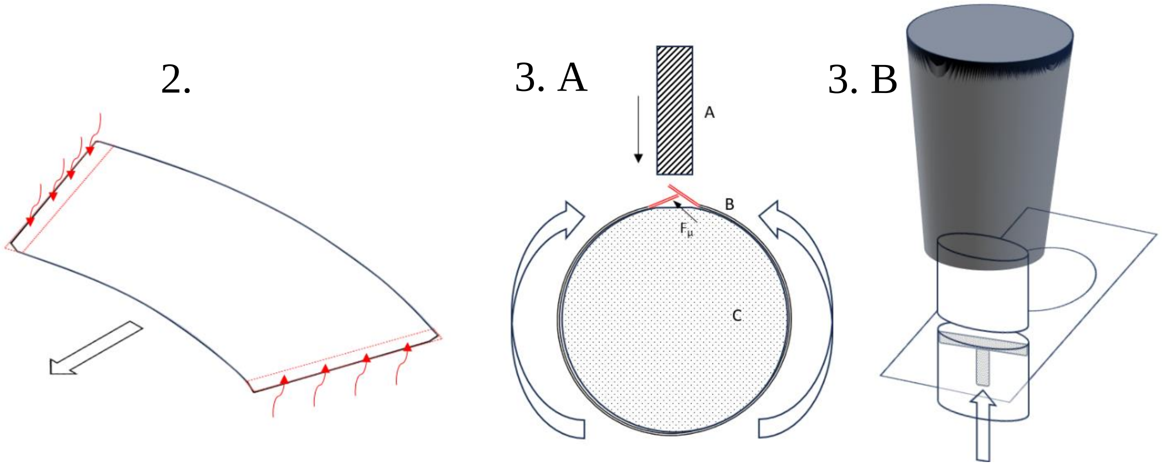

Fig. 1. Stages 2, 3A and 3B of the process. The approximate heated areas are in red. A = sealing tool/ultrasonic sonotrode, B = Wall blank, and C = Mandrel

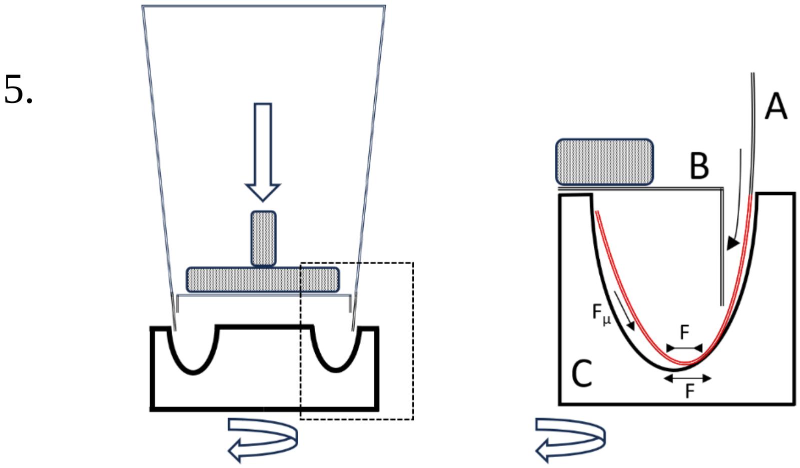

Fig. 2. Principle of the curling stage and forces exerted on the paperboard and coating. The approximate heated portion of the cup wall is in red. A = Wall blank, B = Bottom blank, and C = Curling tool

6. The heated, curled bottom wall is pressed against the bottom blank by either an offset, patterned, rotating knurling tool, or by an outward-expanding segmented sealing tool to form the bottom seal.
7. The bottom sealed cup is transferred to the next set of tools, which apply food-grade oil onto the inside of the top portion of the cup wall to facilitate rim rolling.
8. The rim of the cup is typically formed in 2 to 3 stages by pushing a series of concave dies down onto the top portion of the cup while the cup is being supported by a second, stationary bottom die.
9. Cup machines can feature visual machine vision-based inspection of the cups to separate defective cups from accepted ones. Some defects, however, can easily go

> unnoticed, especially if the top and bottom inspection is used and the defect is located below the rim roll."

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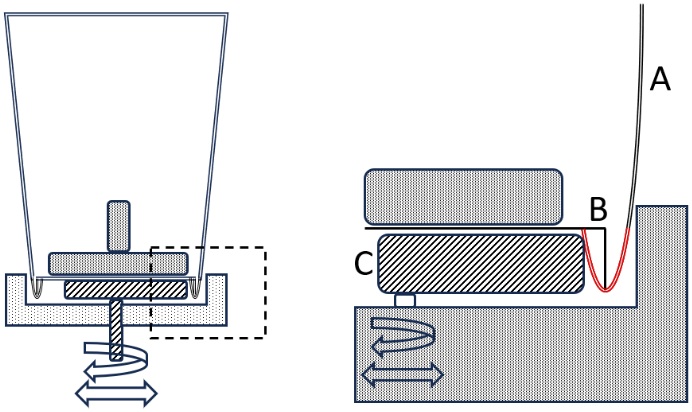

Fig. 3. Principle of the knurling stage using an offset, patterned tool. The heated area of the cup wall is in red. A = cup wall, B = bottom blank, and C = knurling wheel

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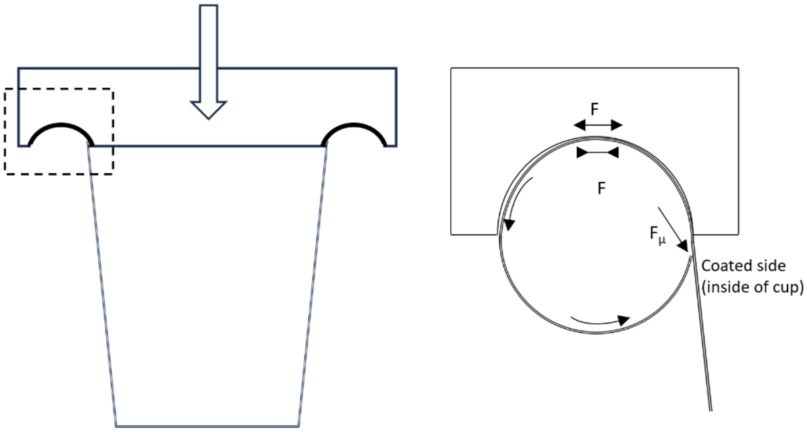

Fig. 4. Principle of the rim rolling stage and forces exerted on the paperboard and coating

The process subjects the cupstock to both mechanical and thermal stresses, the nature of which is dependent on the type of the machine in question. Nonetheless, the general stresses caused by heating, folding, sealing, bottom curling, bottom knurling, and rim rolling are present in all machines. Investigating the critical factors affecting the manufacturing chain is vital to ease the entry of non-fossil-based materials into the market. The problems caused by differing material behavior are exacerbated by the large differences between machinery used by cup makers (small-scale to industrial), which places different requirements on materials, *e.g.*, one machine may suffer more from high friction between materials and surfaces due to a sliding blank track. Another may use suction cups to transfer the blanks, partially avoiding the effects of frictional forces.

The most mechanically demanding stage of the process is the rim rolling stage, as the 340 µm thick paperboard is rolled into a circular shape with a diameter of 2 to 3 mm, which is incredibly demanding on the section of the rim where the layers of the side seam overlap. This stage requires the deformation of the paperboard, namely the delamination of the layers on the inside of the rim roll (Ramasubramanian and Swecker 2001; Upadhyaya and Nygårds 2017). Similar deformation mechanics take place in the bottom curling stage but to a lesser extent due to only requiring a ~180° bend instead of the overlapping, full circle of the rim roll. The bottom of the wall blank is heated before curling, which, at worst, may cause the partially cooled side seam to open after curling due to a spring-back effect if the sealing polymer has weak hot tack strength. This can cause the separated outer part of the side seam to interfere with the knurling process, causing an insufficient seal on the bottom. In all stages of the process, where materials are either sliding against metallic machine surfaces or molds or overlap with themselves, stress is caused by frictional forces. It has been shown that paper-to-metal friction decreases as temperature increases (Vishtal *et al.* 2014), while the opposite is true for polymer-to-polymer friction (Martin *et al.* 2012).

The objectives of the study were to find the most commonly occurring manufacturing defects and to assess the importance of different material properties in the cup manufacturing process as a whole by forming four materials with varying mechanical and surface characteristics and two different coating methods into cups using a high-speed cup machine. In addition to classifying and quantifying any occurring defects, cup dimensions in an attempt to find a relation to material properties were measured.

EXPERIMENTAL

A broad selection of materials with differing frictional properties and coating types was chosen to represent the variety of materials used in cup manufacturing. Included were one- and two-sided materials as well as high- and low-friction materials coated with either extrusion or dispersion coating techniques. A one-sided polyethylene extrusion-coated cupstock was used as the reference material (Material 1) due to the prevalence of comparable materials in commercial disposable cups. All materials were stored in a constant climate chamber at 23 °C/50% relative humidity (RH), as is recommended by most manufacturers. The moisture content of the wall blanks was measured by weighing unconverted blanks in an Adam Equipment PMB 53 moisture analyzer. The chosen materials and their fundamental properties in both machine direction (MD) and cross-direction (CD), as well as used measurement standards, are listed in Tables 1 and 2. Measurements were conducted in standardized conditions of 50% RH and 23 °C. The coefficient of friction was determined for the coated side, or reverse side/inside of the cup for 2-sided coated materials, against a steel surface.

Table 1. Used Cup Materials, Their Grammage, Thickness, and COF

Material	Material Type	Grammage, ISO 536:1995 (g/m^2)	Thickness (µm)	COF of Coated Side/Inside of Cup, ISO 8295:1995		COF of Fiber Side/Outside of the Cup, ISO 8295:1995	
				MD	CD	MD	CD
1	1-side extrusion coated paperboard	248	336	0.509	0.512	0.215	0.213
2		257	352	0.262	0.259	0.203	0.202
3	2-side dispersion coated paperboard	252	344	0.704	0.709	0.498	0.507
4		245	335	0.415	0.429	0.174	0.168

Table 2. Key Mechanical Properties of Used Cup Materials

Material	Tensile Strength, ISO 1942-2:1994 (kN/m)		Compression Strength ISO 12192:2002 (kN/m)		Bending Stiffness, SCAN-P 64:90 (mN)	
	MD	CD	MD	CD	MD	CD
1	20.1	9.1	3.836	2.668	226	89
2	18.5	10.1	3.832	2.847	257	111
3	17.8	9.0	3.560	2.424	217	90
4	17.04	8.76	3.531	2.575	226	94.9

A Debao NewTop 138s commercial, high-speed cup forming machine (New Debao Machinery, Zhejiang, China), which has a maximum production speed of 140 CPM, was used to convert the coated paperboard blanks into 8 oz/250 ml hot beverage cups. The machine is shown in Fig. 5.

Fig. 5. A cup manufacturing machine was used for the study

The process of cup converting is similar in slow and fast machines, and the main differences are found in blank transfer between stages and techniques used to prevent the opening of recently sealed seals due to hot tack effects. Each stage of the converting process could be adjusted either mechanically or *via* the machine's software. Adjustable process parameters included hot air temperatures and production speed. The process parameters were chosen to suit each material while keeping the production speed constant for comparison purposes. The same sealing temperatures were used for both the preliminary run (run 1) and the post-adjustment run (run 2) for each material. At the same time, changes were made to some mechanical adjustments to promote runnability differences between materials. The width of the side seam was chosen as the main dimension to be adjusted, as side sealing is the first converting stage found in the process, affecting all subsequent stages as well. The process parameters used and measured moisture content for each material are listed in Table 3. The moisture content of each material was at an acceptable level, albeit slightly lower than reported values for moisture content on delivery.

Table 3. Process Parameters and Measured Moisture Content of Cup Materials Before the Production Runs

Material	Hot Air Temperature		Production Speed (CPM)	Moisture Content (%)
	Side Seam (°C)	Bottom Seam (°C)		
1	425	465	140	6.4
2	400	400	140	6.2
3	325	375	140	6.0
4	375	400	140	6.1

The trial runs were conducted in two batches: In the first one, mechanical machine adjustments were made, including the side seam sealing position on the mandrel and height of the curling, knurling, and rim rolling tools, which were confirmed to result in a majority of defect-free cups using the reference material. The side seam sealing position was then changed for the following manufacturing run, and the rest were adjusted accordingly to make the forming process more demanding on the material. Manufactured cups from both runs were measured to verify the change in dimensions. The average rim width and height, upper outside diameter, inner bottom diameter, side seam width, and cup height from six defect-free cups of each material were measured. Caliper gauges were used for all measurements but cup height, which was measured using a tabletop analog height gauge seen in Fig. 6. Any defects found that were suspected to potentially because leaks were confirmed by filling a maximum of 5 defective cups with 90° C coffee for 15 min to confirm their liquid tightness. The adjustments aimed to modify the width of the side seam area and, thus the geometry of the cups and their fit on the subsequent tools should also be affected. Because of the differing surface and mechanical properties of the materials, an increase in the frequency of different defects was to be expected.

Fig. 6. The device that was used to measure cup height

RESULTS AND DISCUSSION

Dimension-based Analysis

Both cup manufacturing runs were successful in producing a distribution of both defect-free and defective cups, with substantial differences between each run. As expected, the second runs with an adjusted side seaming position resulted in changes to some of the dimensions of the cup, namely the side seam and the rim roll. Measured dimensions for both manufacturing runs and changes between them are presented in Tables 4 to 6 and Fig. 7.

Table 4. Cup Dimensions of Run 1

Material	Rim Width (mm)	Rim Height (mm)	Upper Outer Diameter (mm)	Bottom Diameter (mm)	Side Seam Width (mm)	Cup Height (mm)
1	2.89	3.29	79.47	54.59	7.47	88.74
2	2.89	3.44	79.43	54.55	7.56	88.76
3	2.94	3.29	79.40	54.35	7.43	88.55
4	2.89	3.24	79.42	54.59	7.80	88.71

Table 5. Cup Dimensions of Run 2, after Adjusting the Side Sealing Position

Material	Rim Width (mm)	Rim Height (mm)	Upper Outer Diameter (mm)	Bottom Diameter (mm)	Side Seam Width (mm)	Cup Height (mm)
1	2.85	3.22	79.20	54.66	8.06	89.02
2	2.85	3.30	79.42	54.56	7.81	89.02
3	2.93	3.29	79.38	54.48	8.10	88.93
4	2.83	3.12	79.25	54.49	8.19	89.13

Table 6. Change in Dimensions Between the Preliminary and Second Run After Adjustments

Material	Rim Width	Rim Height	Outer Upper Diameter	Bottom Diameter	Side Seam Width	Cup Height
1	-1.3 %	-2.3 %	-0.3 %	0.1 %	7.9 %	0.3 %
2	-1.2 %	-4.3 %	0.0 %	0.0 %	3.4 %	0.3 %
3	-0.3 %	0.0 %	0.0 %	0.3 %	8.9 %	0.4 %
4	-2.1 %	-3.8 %	-0.2 %	-0.2 %	4.9 %	0.5 %

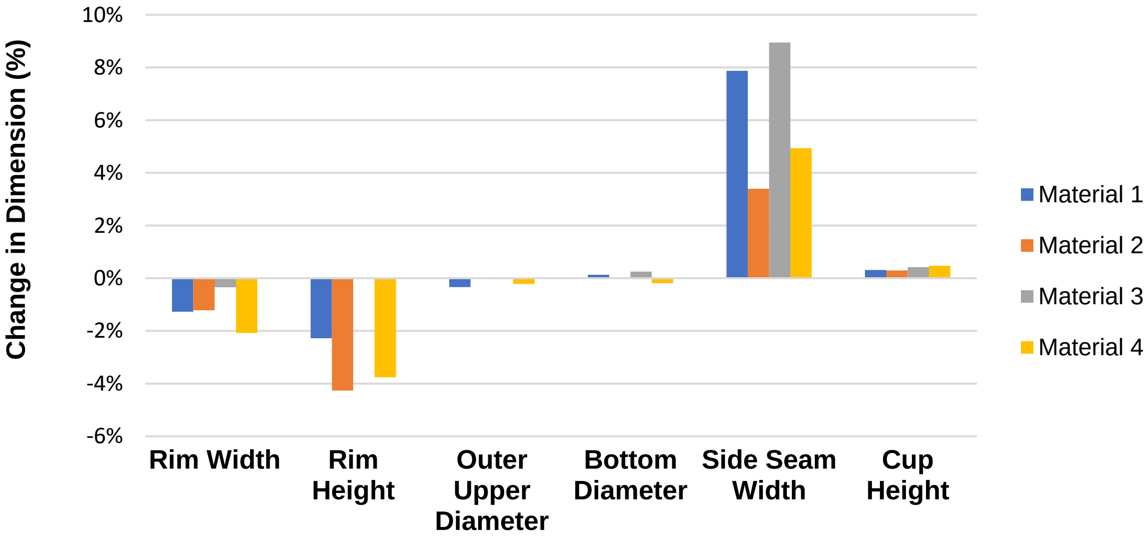

Fig. 7. Percentual change of cup dimensions between the preliminary and second run

The change in top and bottom diameter as well as cup height compared to the first trial run was negligible at 0 to 0.5% for all materials. The degree of change in the width of the side seams was noticeably different between materials: the higher the COF of the material, the higher the change in side seam width, which is displayed in Fig. 8. Bending stiffness in the cross-direction could also have some effect on the carryover of the adjustment, as seen in Fig. 9. The height of the rim rolls was affected more by the adjustments than their width and, similar to the side seam, seemed to be affected by the COF of the materials, as shown in Fig. 10. Overall, the height of the rim rolls was reduced by 2 to 4%, while for Material 3, which also had the highest COF, the rim roll height remained unchanged. Material 2, which experienced the largest decrease in rim roll height had the lowest COF but also the highest bending stiffness in MD. The low COF is most likely the main reason for the change, as it allows the rim roll to be tucked more easily due to less resistance. The effect of bending stiffness on rim roll forming is presumably insignificant compared to COF and possibly the delamination strength of the paperboard.

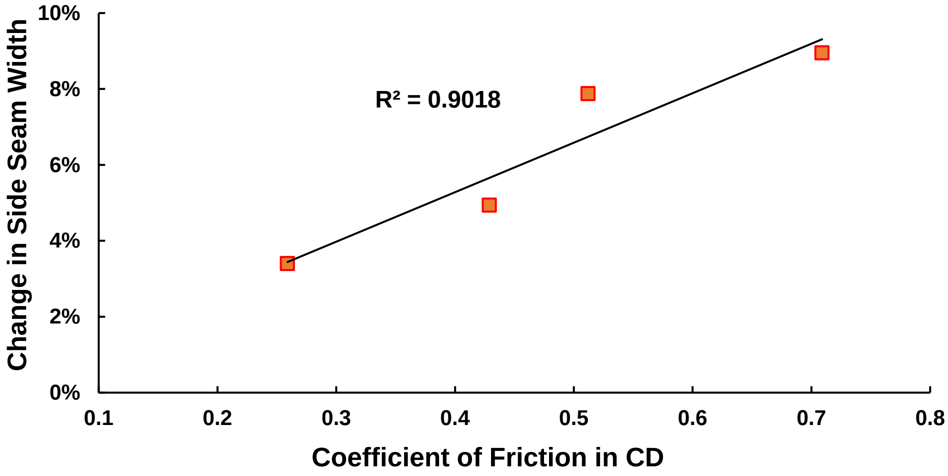

Fig. 8. Percentual change in side seam width in relation to COF of the materials in CD

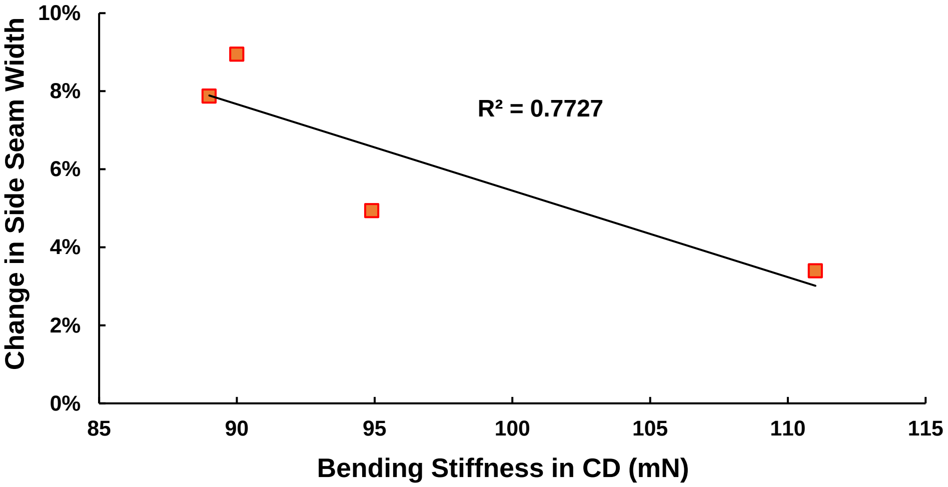

Fig. 9. Percentual change in side seam width in relation to the CD bending stiffness of the materials

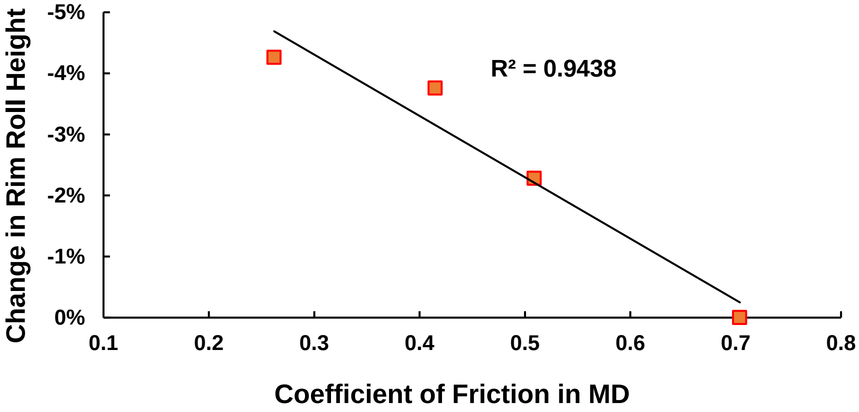

Fig. 10. Percentual change in rim roll height in relation to COF of the materials in MD

Defect-based Analysis

The manufactured cups were categorized according to the primary defect found in the cup. The selection of the main defect was based on its effect on the cup's usability first and shape and appearance as the second and third criteria, *e.g.*, a forming defect exposing additional fibers will override a visual defect, causing no usability or safety issues. Defects were categorized according to their location into either the rim roll area, side seam area, or bottom area. Furthermore, each defect was categorized into visual defects, shape defects, and potential leak-causing defects. Visual defects mainly affect the aesthetic properties of the cup but do not cause issues in subsequent converting stages, *e.g.*, an untucked rim roll. Shape-related defects such as minor buckling of the side seam slightly affect the shape of the cup and could have a negative effect on later forming stages or functionality; *e.g.*, the fit of lids for takeaway coffee could be affected. Leak-causing defects have the potential but are not guaranteed to affect the usability of the cup by compromising the sealing areas of the side and bottom seams, *e.g.*, major buckling of the side seam or bottom insertion issues. The defects found and suspected failure mechanisms are presented in Figs. 11 to 17.

Fig. 11. The rim roll of the cup has split near the side seam, exposing the fiber structure of the paperboard

Rim roll defects

- Split rim: The cup’s rim roll has split, exposing fibers and affecting the roundness of the rim roll negatively. Split rims are often caused by low moisture content due to the reduced tensile properties of the material, a geometry too restricting for the material, or a combination of both. —shape defect.

- Rim roll tuck failure: The tuck of the rim roll has fallen short, possibly due to friction or failure of the side seal near the rim—visual and shape defect.

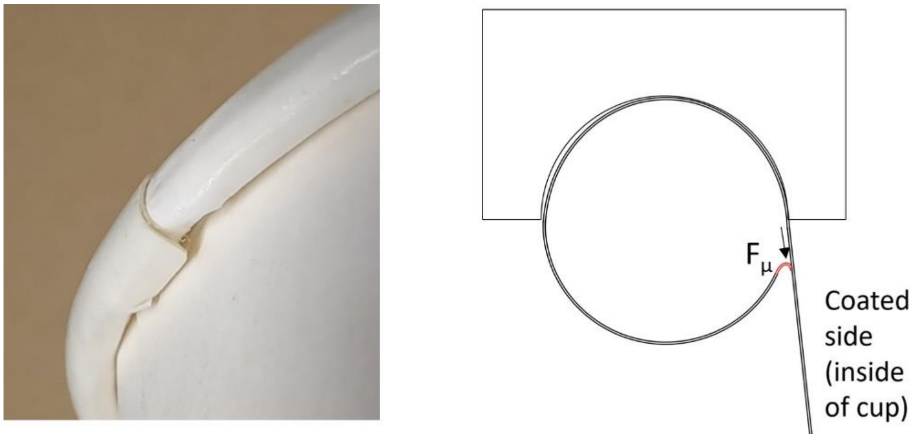

Fig. 12. Rim roll tuck defect and the possible cause

- Rim delamination: The rim roll has partially opened due to delamination of the paperboard layers in the top side seam layer, leaving the bottom half attached and tucked to the rim roll—visual defect.

Fig. 13. Delaminated rim roll with exposed fibers

Side seam defects

- Major buckling of the side seam area: Wall material adjacent to the side seam has noticeably collapsed inwards, affecting the roundness of the cup, likely caused during the side seaming stage, as displayed in Fig. 11. As the displayed failure mechanism can also increase the circumference of the cup by reducing the overlapping area in the seam. Subsequent tools could push the side seam inwards, causing similar buckling—shape defect.

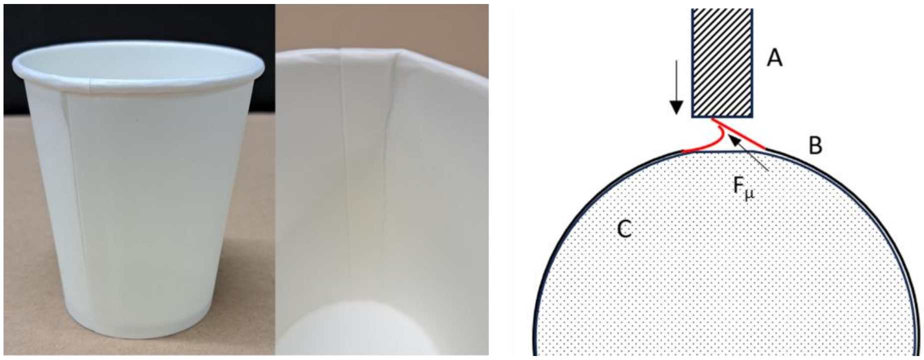

Fig. 14. Cup with a majorly buckled side seam (Material 1) and suspected mechanics of defect formation. A: Sealing tool, B: Wall blank, and C: Mandrel

- Minor buckling: The side seam has slightly collapsed inwards, affecting the cup's roundness slightly. A bad rim roll tuck could cause this due to reduced roundness, as seen in Fig. 12—shape defect.

Fig. 15. Minor buckling of the side seam and rim roll from the outside (left) and inside (right)

Bottom defects

- Buckling: The side seam near the bottom fold has collapsed, causing a noticeable horizontal wrinkle. The cause could be incorrect fit on the bottom forming tools combined with high COF and low hot tack strength, causing them to push up on the cup and thus subjecting the side seam seal to shear while still hot. It possibly affects liquid tightness near the bottom. Visual or potential leak defect—4/5 cups leaked coffee.

Fig. 16. Buckling of the side seam area near the bottom

- Open bottom seam: The side seam seal has failed during curling and/or knurling, causing a gap to form between the sealed portions of the sidewall. It was likely caused by a spring-back effect of the reheated seam in curling, causing the detached part of the side seam to push against the knurling tool, opening the seam—potential leak defect—2/5 tested cups leaked coffee.

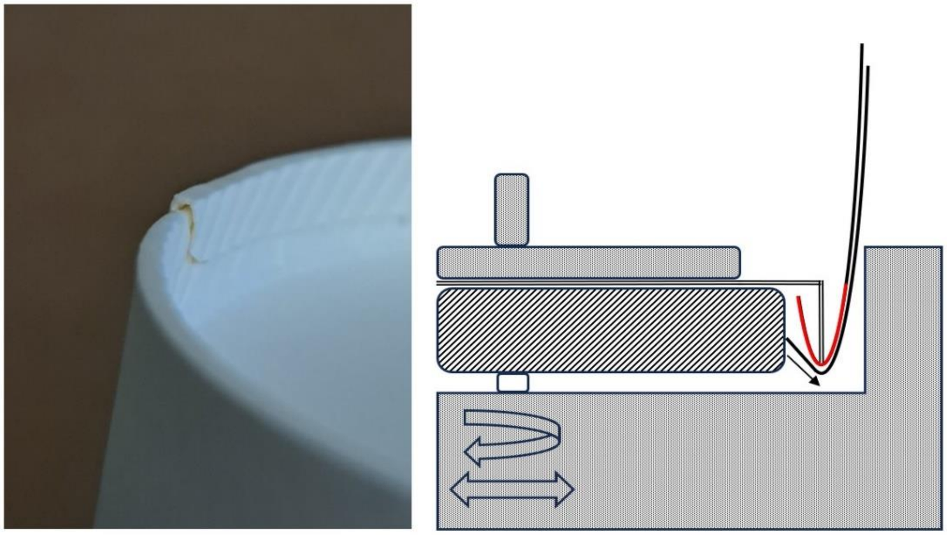

Fig. 17. An opened bottom seam on a cup and a suspected failure mechanism.

The first cup production run before the adjustments resulted in a majority of defect-free cups for the reference material (1), with the high COF dispersion coated material (3) having the largest share of disqualified cups at 40%. The categorization of the defects found is presented in Table 7.

No material reached a zero percent defective rate. However, of the defects found in materials 1 and 2, only the singular buckling defect of the bottom in Material 1 could potentially lead to leaks, making most of the cups usable. A zero defect run would be expected, provided that the machine was adjusted for running one specific material. The most notable defects were bottom forming issues in Material 3, which could be explained by its high friction coefficient of 0.704 in MD and two-sided coating, as the wall material is heated before bottom forming, causing increased friction against the tools and inserted bottom blank. The increased friction between the heated outer cup surface and the curling tool could also explain the high prevalence of these defects. Material 4 faced issues with rim roll forming, with all recorded defects occurring in the rim area. The defects could be explained by the low tensile strength of the material combined with its tendency to form smaller rim rolls compared to other materials. The low moisture content of the paperboard can also because rim rolls to split, but the measured moisture content of all materials was at an acceptable level. The delamination in rims could be caused by a low interlaminar strength combined with a high seal strength, for example, causing the outer paperboard layer of the side seam to delaminate instead of opening the seam around the rim roll area. This suggests that the rim roll geometry was too tight for the material, preventing a proper tuck. The defects found in the cups produced in the second, more demanding trial runs are presented in Table 8.

Table 7. The Defects Found in the Cups Produced in the First Trial Run

Defect types – Run 1									
		Rim roll		Side seam		Bottom		Total	
Sample	**Delamination**	**Tuck**	**Split rim**	**Buckling (minor)**	**Buckling (major)**	**Buckling**	**Open seam**	**Defective**	**Passed**
Material 1	0	1	5	2	0	1	0	9	91
Material 2	4	1	0	6	0	0	0	11	89
Material 3	0	0	0	0	0	22	18	40	60
Material 4	11	0	13	0	0	0	0	24	76

Table 8. Defects Found in the Cups Produced in the Second Trial Run After Adjusting the Side Seaming Position

Defect type - Run 2 (wider side seam)									
		Rim Roll		Side Seam		Bottom		Total	
Sample	**Delamination**	**Tuck**	**Split rim**	**Buckling (minor)**	**Buckling (major)**	**Buckling**	**Open Seam**	**Defective**	**Passed**
Material 1	0	5	3	6	6	0	0	20	80
Material 2	2	1	6	1	3	0	0	13	87
Material 3	1	32	0	1	0	2	34	70	30
Material 4	16	0	6	5	0	0	0	27	73

An overall increase in the number of defective cups was seen after adjustments. The change was most noticeable in Materials 1 and 3, with a decrease of 12% and 50% in accepted cups, respectively. The increase in the share of defective cups was the smallest for Material 2, which also experienced the smallest change in side seam width and had the lowest COF. A high COF seemed to increase the share of defective cups after adjustments, as seen in Fig. 18. Even so, all defects are not likely caused by solely frictional forces. For Material 1, major buckling defects of the side seam appeared, and the frequency of minor buckling defects of the side seam increased. COF alone is likely not the cause, as Material 3, with an even higher COF, did not see a similar increase and instead experienced more difficulties in bottom forming and rim roll forming.

The rim roll tuck defects and bottom insertion defects of Material 3 suggest a low hot tack strength or lower seal strength, which could alleviate the formation of buckling defects as the partially molten seal surfaces would be subject to shear stress instead of the wall compressing, preventing buckling, thus shifting the stress on the seal area instead. The bottom buckling defects of Material 3 decreased and seemed to shift toward the opening of the bottom seam instead. The buckling of the seam near the bottom is likely the most harmful defect for liquid tightness found in the runs. Nevertheless, both can lead to leaks with a high probability.

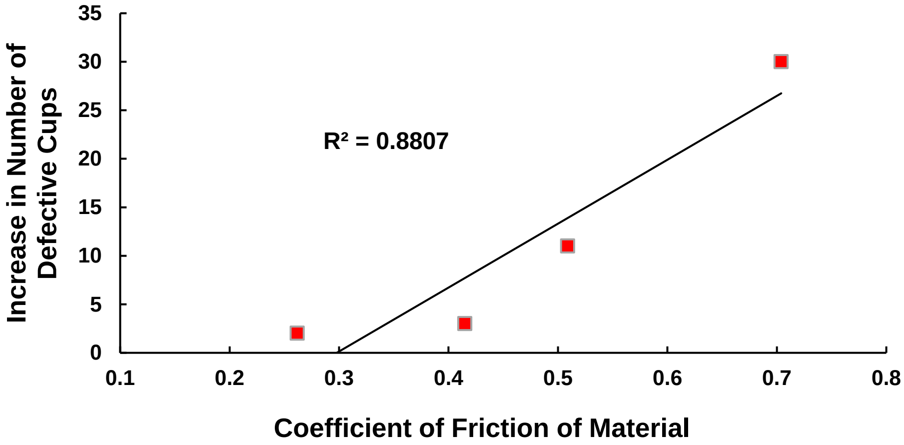

Fig. 18. Correlation between COF and increase in the number of defective cups after adjustments

The measured compression strength of Materials 3 and 4 was slightly lower than those of Materials 1 and 2. Material 3 suffered from buckling issues near the bottom after the adjustments. However, the slightly lower compression strength alone is not enough to explain the bottom buckling defects, as they were not present in Material 4 with similar mechanical properties. In contrast, Material 4 suffered from rim roll delamination, which would suggest low interlaminar strength but high seal strength, which could prevent the side seam from opening, thus avoiding buckling despite its lower compression strength.

In summary, the COF of materials affects their response to dimensional adjustments and the occurrence of defects, as many stages are dependent on the interaction of material and machine surfaces. A high COF made the materials resistant to adjustments to the rim roll, while the side seam area was more receptive to adjustments. When the cup size was slightly reduced through mechanical adjustments, low-friction materials were more resistant to the occurrence of defects, while high-friction materials suffered more. Bending stiffness also seemed to be correlative to some dimensional changes. Most defects recorded in the manufacturing runs were mainly explainable by friction. In future studies focused on material runnability in terms of mechanical properties, the dominating aspect of friction should be considered by using the same polymer coating on different grades of paperboard, for example. Varying the effects of heat-sealing-related properties such as hot tack strength and seal strength would be worthwhile to study as their potential effects in a high-speed process could be noteworthy. As the production speed affects the peak temperature and cooling of the blanks due to the time spent on heating and transferring the blanks between stages, further affecting frictional and mechanical properties of the materials, studying the effects of variable production speeds and thereby blank velocity could be useful. Tackiness of the coating material caused by heating should also be included, as it could have a major effect on the coating-coating and coating-paperboard friction forces found in the process.

This study examined the relationship between material properties, the occurrence of defects, and the dimensions of cups manufactured *via* an industrial-scale cup machine from four coated paperboards with varying surface and mechanical properties were examined. By adjusting the size of the resulting cups slightly between two trial runs, clear differences in defect formation and changes in cup dimensions were seen between materials. Thus, the goals set for the study were achieved.

CONCLUSIONS

1. The coefficient of friction (COF) of a material seems to be the most indicative property of issues faced during production, as most production stages subject the material to sliding friction forces. A high COF can prevent the successful execution of at least the side sealing and rim rolling stages, while a very low COF could cause issues with the adherence of the cup walls to the male tools on the bottom forming revolver. Besides bending stiffness, other strength properties of the materials did not show a strong correlation with defects or dimensional changes. Due to generally lower glass transition temperatures and mechanical properties of biobased polymer coatings compared to conventional ones, the frequency of defects in novel material is expected to be higher due to increased surface deformations. Reducing the amount of sliding in the process through machine design could help counteract this effect.
2. High bending stiffness combined with a high COF could be problematic in the manufacturing process, specifically in the rim rolling and curling stages. Based on the present findings, developing baseboards in tandem with novel coatings, in addition to avoiding excessive heating or using ultrasonic sealing where possible, could help mitigate the occurrence of defects.
3. Separating the effects of different material properties in cup manufacturing is complicated due to the apparent dominance of COF and the high-speed and consecutive forming stages of the process. These factors also make laboratory-scale testing for sealability and runnability challenging. Short dwell-time sealing tests with reasonable temperatures, as well as testing of the mechanical and surface properties of materials, would be most indicative of a material’s performance.

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