Evaluation of folding effects on coating damage

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ABSTRACT: Barrier coatings on paperboard need to maintain integrity during converting and end-use for effective barrier performance. Folding is one of the most common deformations during converting; however, factors that affect damage during folding are not well defined. This is partly because methods to fold specimens and characterize damage are not standardized and the results are generally not transferable.

In this work, we describe a method to fold paper specimens precisely and reproducibly. The keys to folding include using a defined geometry and controlled deformation. Multiple methods can be used to quantify damage; in this case, we use differences in permeability as a measure of how the coating becomes more open. Damage is sensitive to the degree of compression after the initial folding. Using a shim for support provides a defined amount of compression and minimizes the sensitivity to the applied pressure.

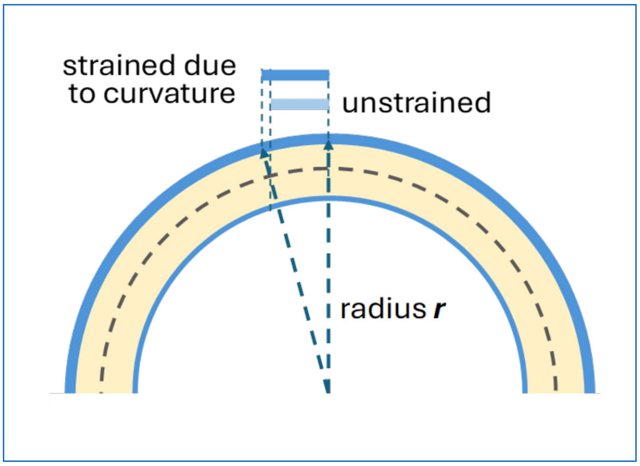
Application: This method advances the development of coating for paperboard applications by improving the transfer of results and knowledge. Through it, results will be more reproducible and meaningful, which will build confidence in the generated knowledge.

Paperboard is a ubiquitous packaging material. Replacing plastic in packaging can be limited due to barrier demands for certain packaging applications. Coated paperboard can provide acceptable barrier performance; however, it is important that the performance is maintained through converting and end-use [1]. Converting is known to cause damage to coatings through creasing and folding; however, factors that affect damage are not well defined [2]. This is partly because methods to prepare specimens and characterize damage are not standardized, and the results are generally not transferable.

Creasing and folding transforms flat paper into three dimensional structures [3]. Creasing is the process of locally delaminating and stretching the paper to define a fold line and to make it easier to fold, while minimizing the potential for surface damage. Folding is the process of bending paper to create a permanent angle along a fold line, also known as the crease. Ultimately, folding creates a tip at the fold line where the curvature is localized. The outer surface of the tip is under tension, idealized as shown in **Fig. 1**. When the strength of the coating at the tip is exceeded by driving factors (such as stress, strain, or energy), the coating will be damaged.

Evaluating coating damage during folding helps to identify optimum coatings and substrates for barrier applications. Factors that affect damage include physical properties and structure of the coating and substrate, as well as creasing and folding dynamics. Useful knowledge from studying coating damage includes:

- Identification of key material properties and optimum structure.
- Clarification of the driving factors and failure mechanisms, which can be used to improve properties and structure.
- Quantification of an operating window (damage initiation and maximum damage), which helps define suitable applications for the coated paperboard.
- Transferability of laboratory results to industrial production.



1. Curvature idealized as a segment of a circle.

A foundation for all of this is a meaningful and reliable fold test.

Methods to fold specimens to evaluate coating damage are discussed in [2,4]. All methods include a technique for folding and may involve creasing before folding and additional compression after folding. Compression further flattens the folded structure to more clearly define the fold line and to increase the permanence of the fold. Compression is included in this study because it can be an integral part of the folding process or an easily applied additional step. Creasing was not included to minimize variables.

Folding techniques include:

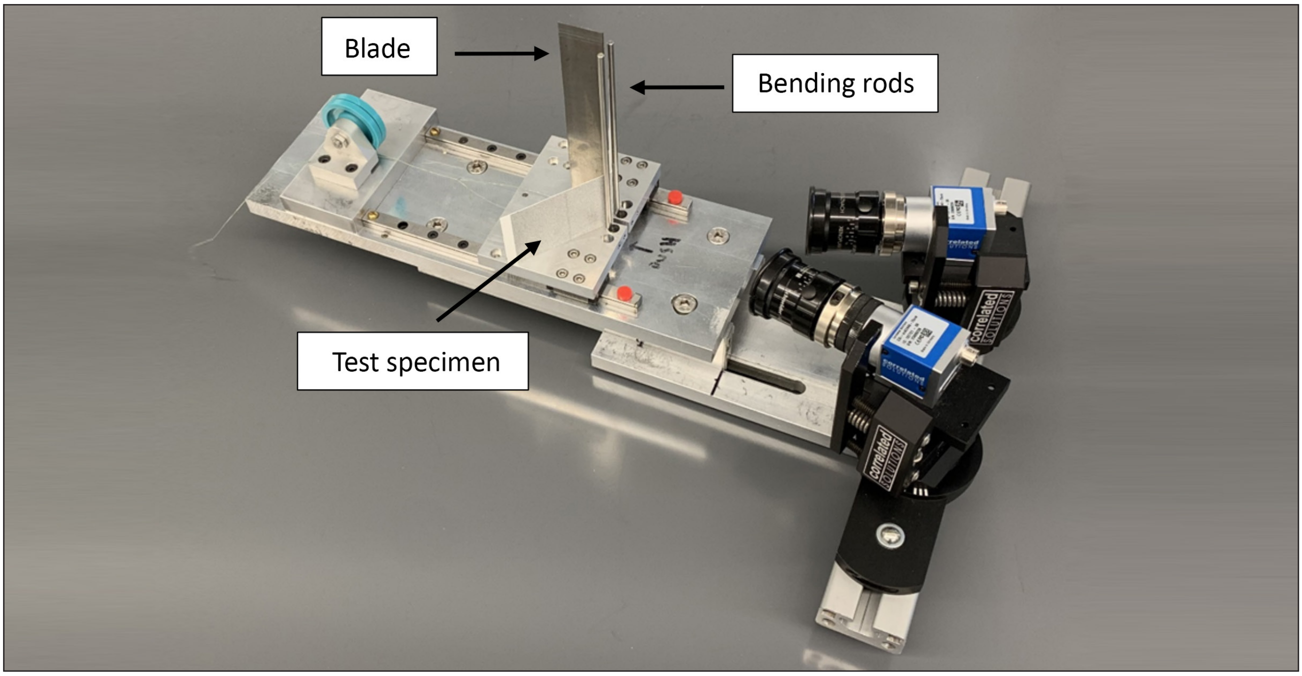
- Manually folding [5,6].
- Folding using a mechanical device produced for other purposes, such as:
  - Prüfbau printability tester [7]
  - Bending stiffness tester [8]
  - Calender nip [9]
  - Water retention meter [10]
  - IGT tester [11]
- Folding using a device custom-built for observing the surface of the specimen during folding such as light microscopy [12] or digital image correlation (DIC) [13].
- Dedicated folding machine, laboratory-scale [14,15] and industrial-scale [4].
- Manually wrapping the specimen around rods of decreasing diameter [16], which defines a radius of curvature at which damage initiates.

Generally, the purpose of using mechanical assistance is to produce repeatable deformation; preferably, the folding mechanism should be relatively simple and easy to define to facilitate transferability and to improve understanding of the factors that drive damage. Compression techniques after folding include a roller [5]; nip under spring load [8]; and static weight [6]. Any subsequent compression can increase the curvature and tension at the outer surface and potentially can crush the fold tip. While compression may be considered a natural extension of folding, the sensitivity of damage to the type and magnitude of compression is unclear, which makes interpretation difficult.

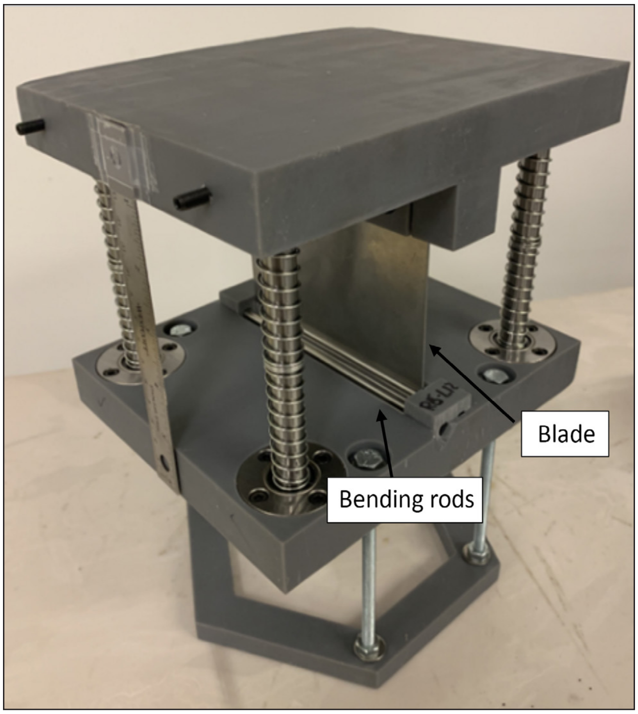
For transferability to different systems, it is important to quantify the driving factors that correlate with damage, which may be curvature, tensile strain, or tensile stress. In principle, curvature can be calculated from the folding geometry and amount of deflection. However, this is only valid at small deformations, and the point at which the actual measurement deviates from calculation is unclear, not to mention the extent of the deviation. Using further assumptions, tensile strain and stress can be calculated from curvature; needless to say, the uncertainty will be further increased.

The alternatives to estimating deformation are to make direct measurements of curvature and strain, such as described using DIC in [13], or by forcing the fold to a specific amount of curvature, such as described by wrapping samples around a rod in [16]. While powerful, DIC requires special equipment and can be time consuming, thus it is not necessarily practical. Forcing to a specific curvature is a relatively simple approach and was pursued in this work as part of the evaluation of compression.

Methods to assess coating damage due to folding have largely involved a qualitative ranking or quantitative measure of cracks, with strength loss and changes in barrier performance also used [2]. The purpose of this work was not to evaluate measures of damage, but to use reasonable methods to evaluate folding. To do this, two different types



2. Folding apparatus used in conjunction with digital image correlation (DIC) measurements [13]. The bending rods move horizontally to fold the specimen.



3. Fold test (FT) apparatus for manually folding samples. The blade moves vertically to fold the specimen.

of measurement were used: differences in air flow, as a surrogate of barrier performance, and crack area, as a visual assessment. These are further described in Materials and Methods.

The purpose of this study was to evaluate the effect of folding conditions on coating damage. The first part consisted of folding specimens using a range of folding geometries and amounts for folding deflection. The second part consisted of compressing folded specimens using a roller, with and without a shim in the fold. Damage was quantified with both air flow measurements and crack area.

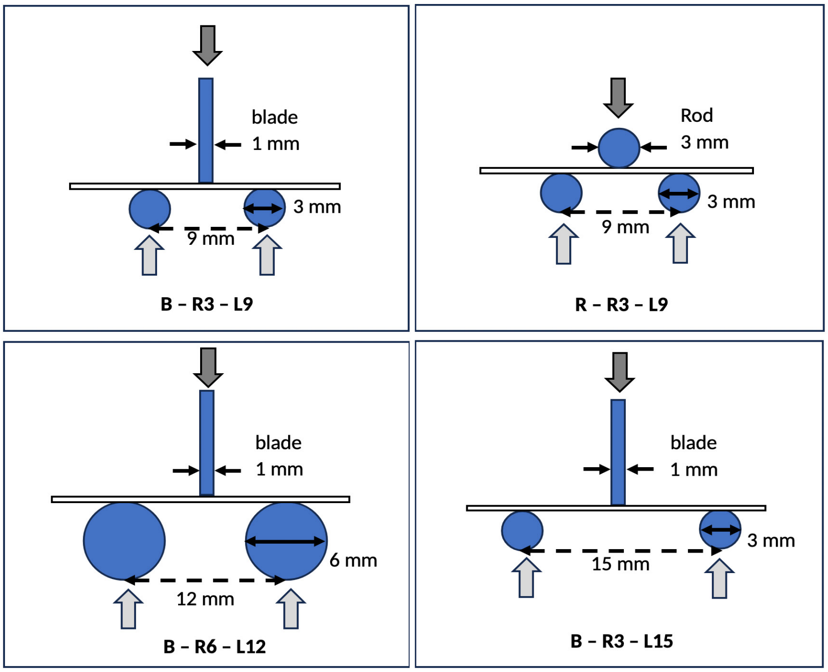
MATERIALS AND METHODS

Two coated solid bleached sulfate (SBS) paperboard grades were evaluated: A, 0.31 mm (0.012 in.); and B, 0.40 mm (0.016 in.).

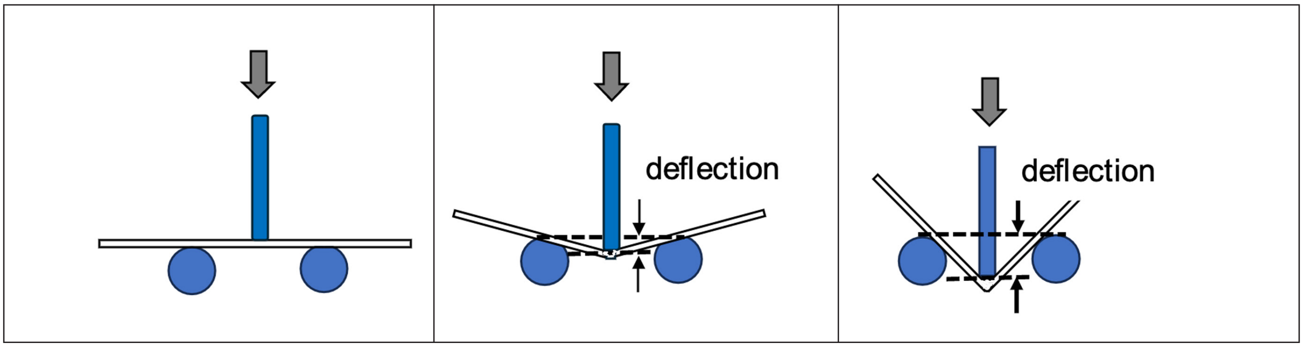
Test specimens were cut to 75 mm x 100 mm (3 in. x 4 in.) and were pre-conditioned at 20% relative humidity (RH) and then conditioned at 50% RH. Two apparatus were used for folding, as shown in **Fig. 2** and **Fig. 3**. Specimens were folded following the geometries shown in **Fig. 4** to different amounts of deflection (**Fig. 5**) and then evaluated. Specimens were folded along the cross-machine direction (CD) and machine direction (MD) fold lines, as shown in **Fig. 6**.

In the second part of the work, folded specimens were compressed using rollers of different weights and with shims of different thicknesses in between the folded surfaces (**Fig. 7**). Based on the shim (t_s) and paper (t_p) thickness, the curvature (κ) was calculated from the inverse of radius (R) using the following equation:

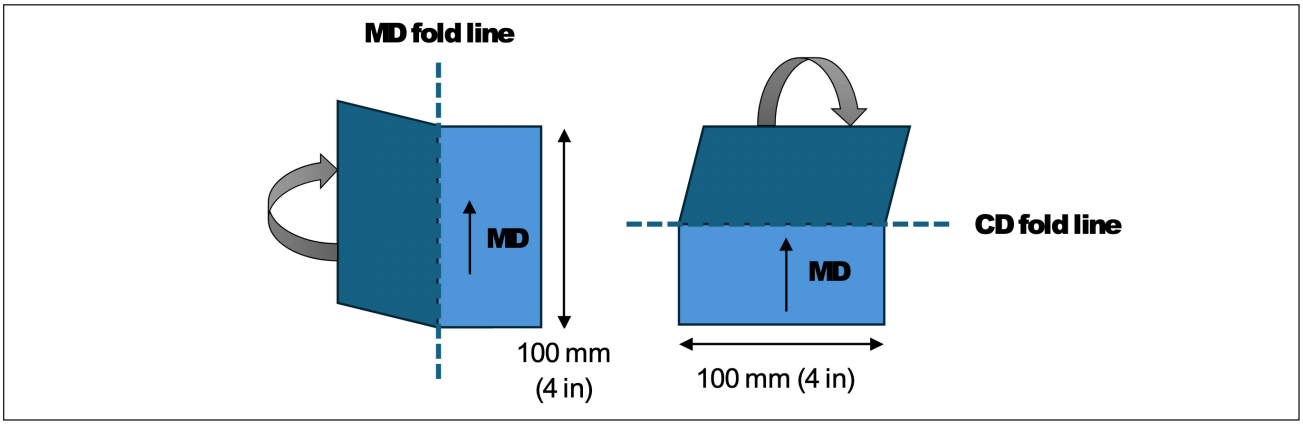
$$\kappa = \frac{1}{R} = \frac{1}{\left(\frac{1}{2}\cdot t_s + t_P\right)} \quad [1/\text{mm}] \qquad (1)$$



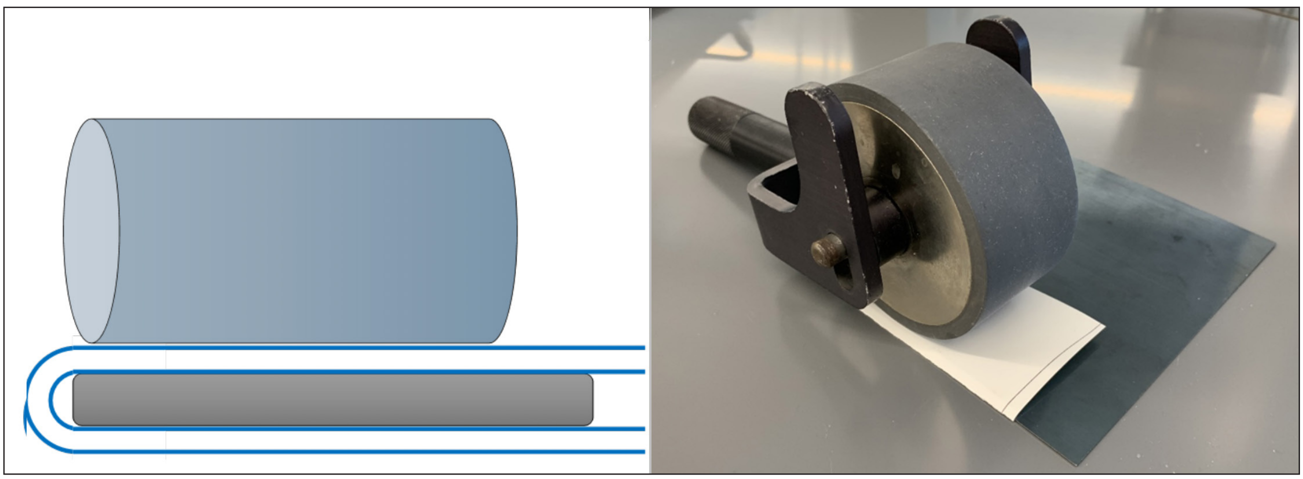
4. Geometries of the vertex and bending rods. The nomenclature describes the bending vertex (B: blade; R: rod), bending rods (R3: 3 mm; R6: 6 mm), and the bending length (L9: 9 mm, L12: 12 mm, L15: 15 mm).



5. Amount of deflection during folding.



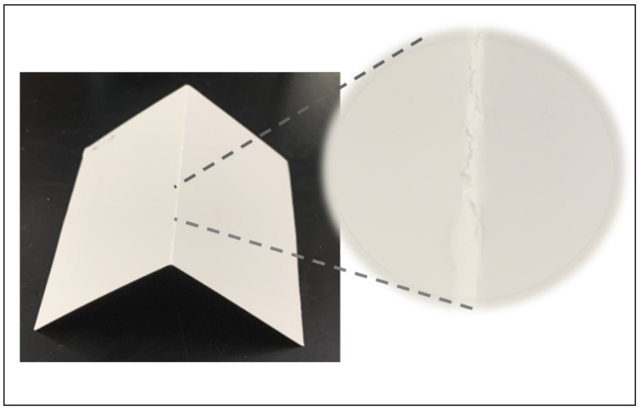
6. Definition of orientation of fold lines (MD: machine direction; CD: cross-machine direction). The MD folding line is also referred to as the longitudinal line, and the CD folding line as the transverse line.



7. Compressing samples after folding. Shims of different thicknesses are used to control the amount of compression.

Figure 8 shows an example of a specimen after folding. Damage was quantified using both air flow measurements and image analysis. Gurley air resistance (s/100 mL) [17] was measured on all of the specimens because it is a relatively quick method, while image analysis was used on a select few. The air resistance value was converted to give permeability in units of mL/min; the permeability increase was then calculated as the difference with the permeability of a non-folded sample. Ten specimens were folded at each condition and two measurements were taken on each specimen, for a total of 20 measurements for each data point. Error bars on charts are 95% confidence intervals.

Crack area on folded and compressed samples was quantified using image analysis (see [4] for a recent review of image analysis of coating cracking). Strips were printed with water-based black ink using a Phantom QD Proofer (HarperScientific; Charlotte, NC, USA), 12.25 BCM. These were then pre-conditioned at 20% RH and conditioned at 50% RH prior to folding using methods described previously. Images of the fold line were generated from a Per-

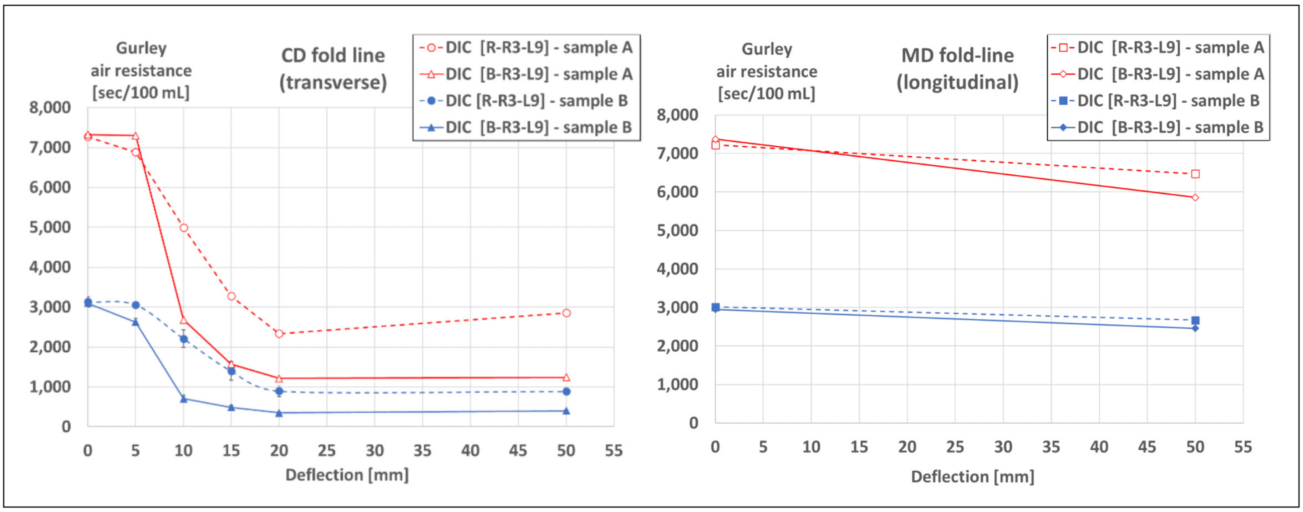


8. Example of a specimen with severe damage.

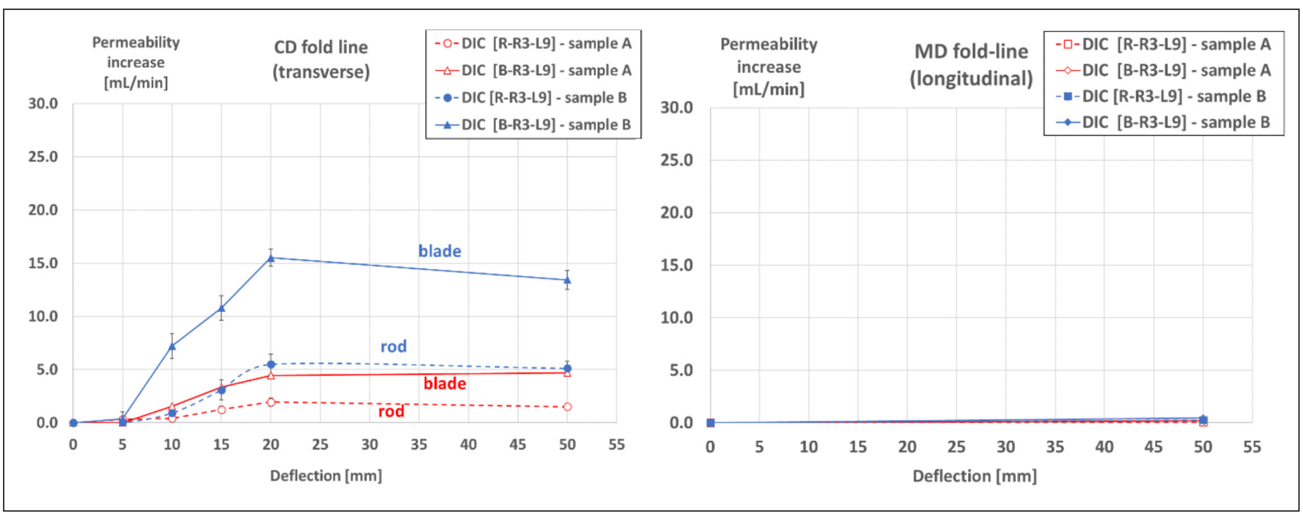
fection V700 Photo flatbed scanner (Epson; Nagano, Japan), 8 bit gray scale, 1200 dpi (Pal et al. showed that there is not a substantial difference in in cracked area across a resolution range of 1200 to 4800 dpi [4]). A jig held the specimens with the fold line at 90° against scanner surface (the angle will have an effect [4]; 90° was chosen to match the angle in many applications). Images were analyzed using Image Pro 11 software (Media Cybernetics; Rockville, MD, USA). Thresholding was set to define features that best matched the cracked areas; features less than 0.0009 mm² were excluded. Results are reported as cracked area (mm²) per length of fold line (cm), same as [18]. We believe this to be a more robust normalization of results as opposed to calculating percent (%) area, which is sensitive to the width of the image.

RESULTS

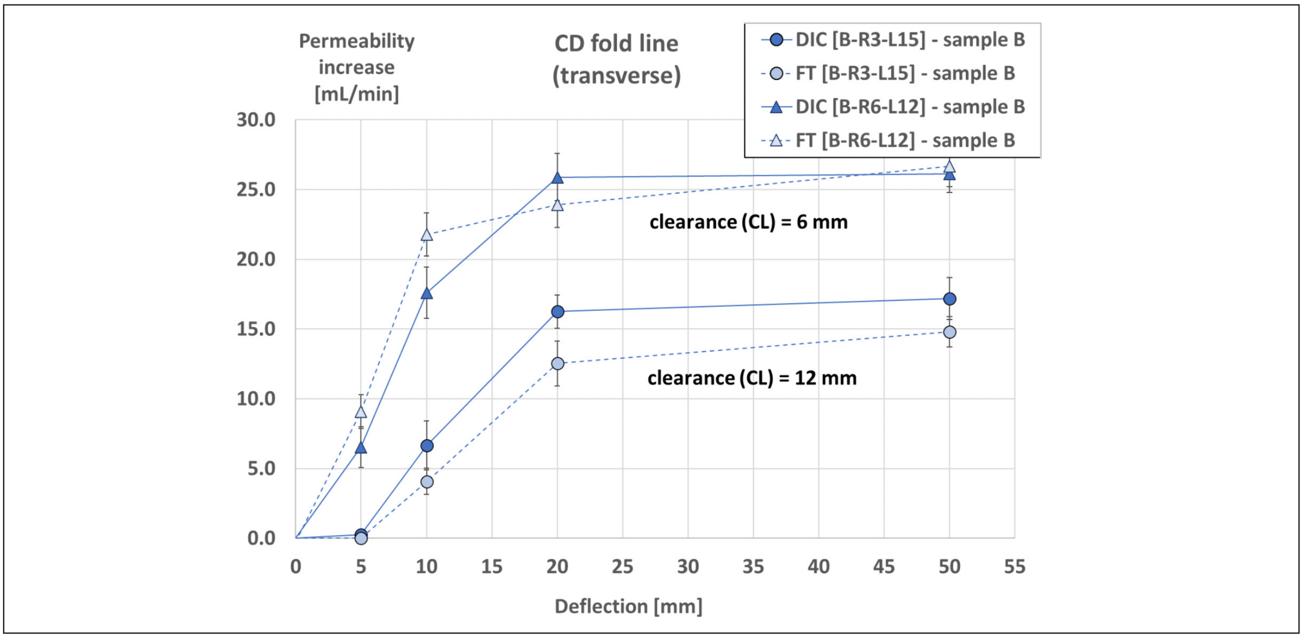
Folding the coated paper samples creates a more open structure, quantified by a decrease in measured air resistance (**Fig. 9**) and an increase in calculated permeability (**Fig. 10**), which is the preferred representation of data in this study. The increase in permeability is caused by an increase in damage to the structure, predominantly



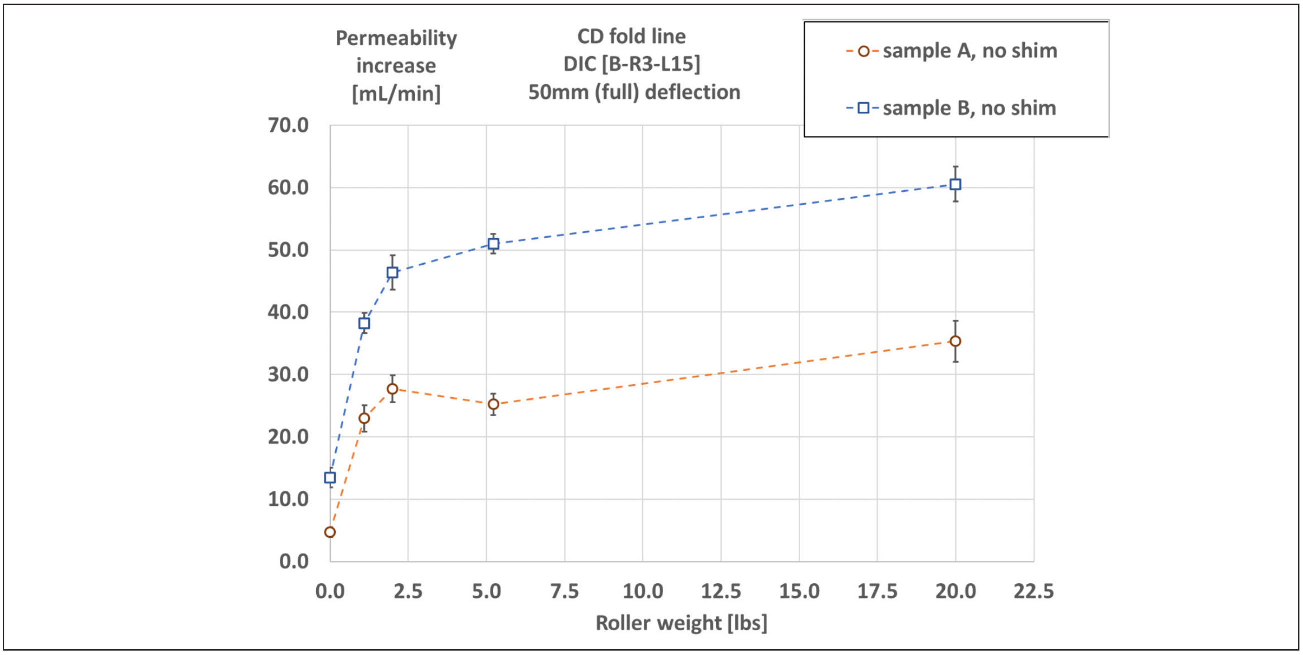
9. Gurley air resistance measured after different amounts of deflection using the DIC device (Fig. 2) with the noted folding geometry (Fig. 4).



10. Permeability increase, converted from results in Fig. 9.



11. Comparison of the two folding devices and folding geometry for the CD fold line. Clearance is calculated as the narrowest gap between the bending rods.

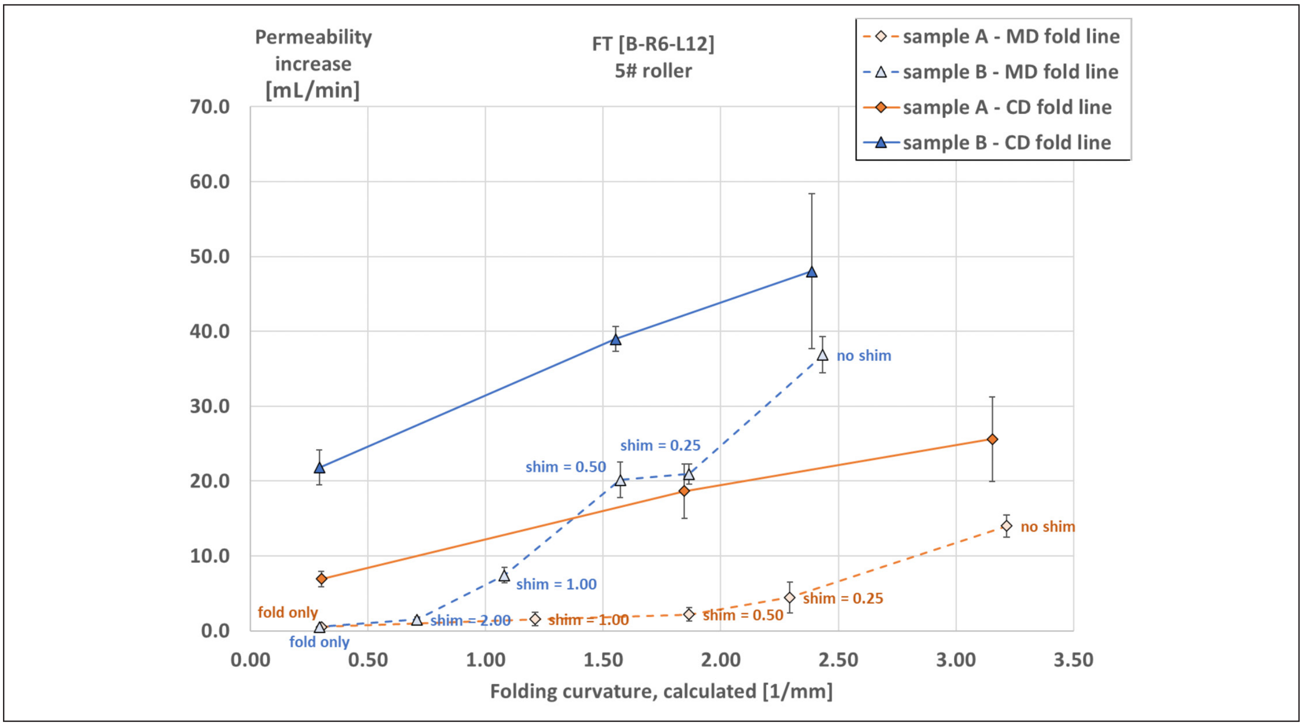


12. Effect of roller weight (no shim) used for compression. The points at the farthest left (roller weight of 0) are values for specimens that were not compressed.

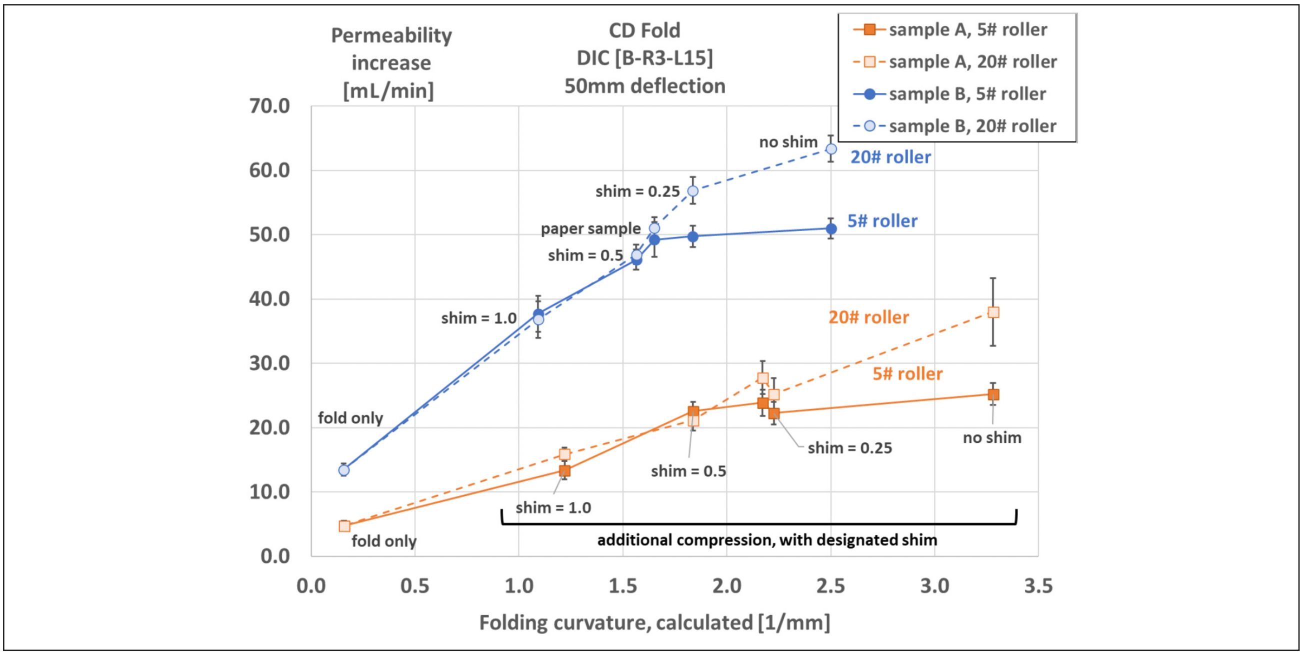
the coating. The paperboard, the folding orientation, and the folding apex all had an effect. Paperboard B showed a greater increase in permeability than Paperboard A. Folding along the CD showed a substantial increase in permeability, while folding along the MD had only a minimal effect. The narrower folding apex (blade) produced a greater increase in permeability.

Figure 11 shows that the fold tester (FT) and the DIC fold device (DIC) produce similar results for two different folding geometries. The folding geometries show that the combination of larger bending rods with the shorter bending length produced more damage, which initiated at a lower amount of deflection.

The effects of compression on folded specimens are shown in **Fig. 12** (no shim) and **Fig. 13** (with shims ranging from 0.3 to 1.0 mm). The permeability increases substantially with a relatively small roller weight, indicating a greater amount of damage. This highlights the importance of keeping the applied weight consistent to make valid comparisons when no shim is used and raises the question



13. Effect of compression with shims of different thicknesses on permeability increase.

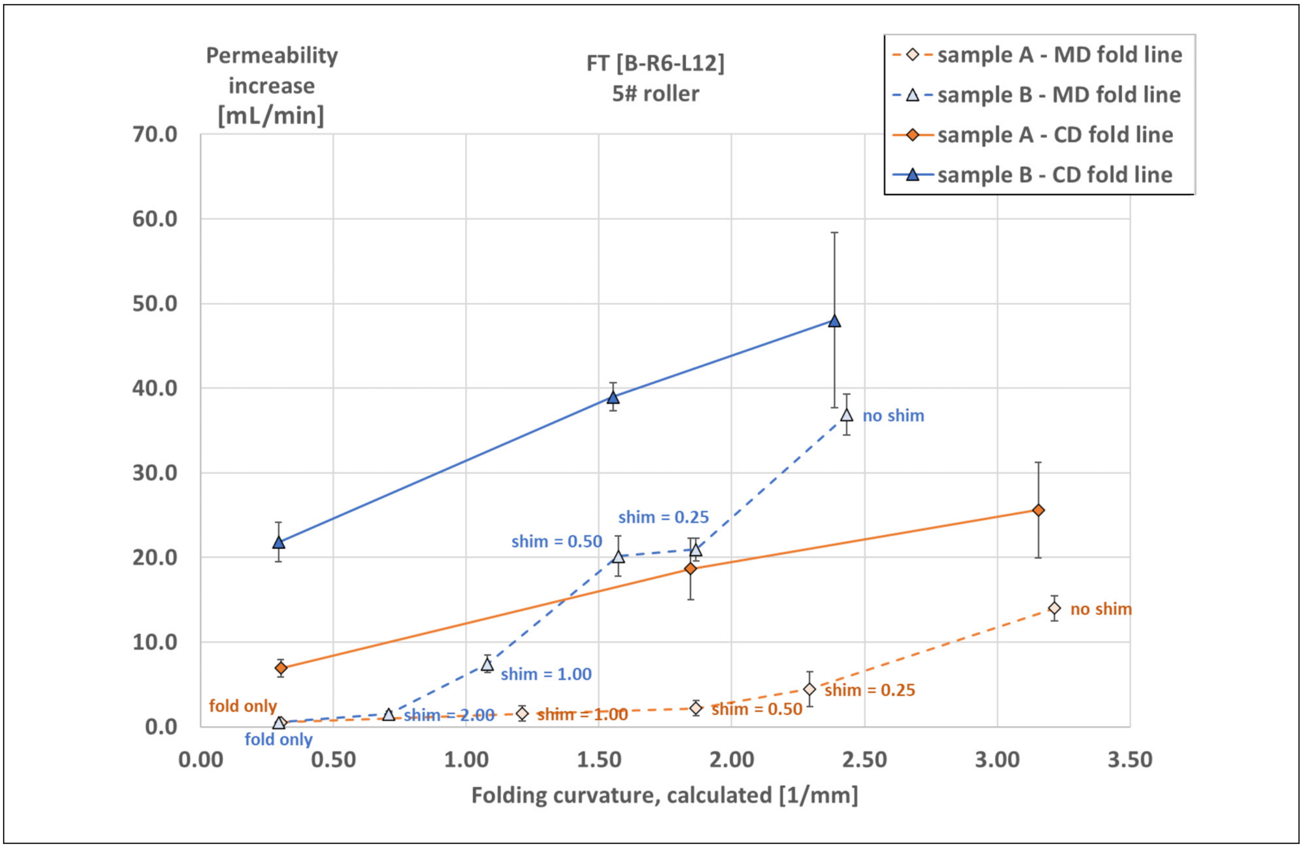


14. The amount of deformation is normalized using a calculated curvature, for folding geometry [B-R3-L15] for a CD fold line.

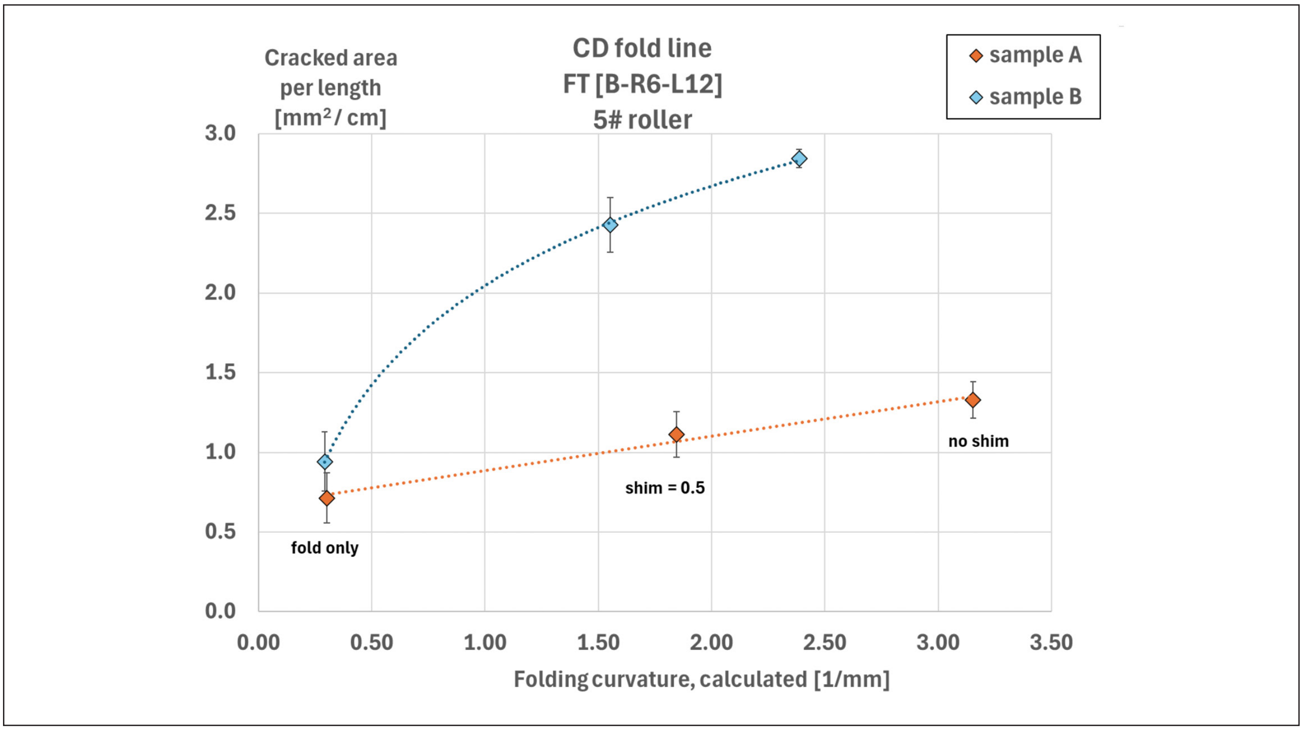
of repeatability when using manual folding. The sensitivity to weight is neutralized using shims that are at least as thick as the paperboard specimen.

Figure 14 and **Fig. 15** show the results in terms of folding curvature (Eq. 1) using two different folding geometries. The damage increases approximately linearly with curvature up to a point, then levels off at a maximum amount of damage. For the CD fold line, the two folding geometries show the same trends for each sample. The MD fold line does not show damage until larger curvatures have been reached, after which it starts to approach the values for the CD fold lines.

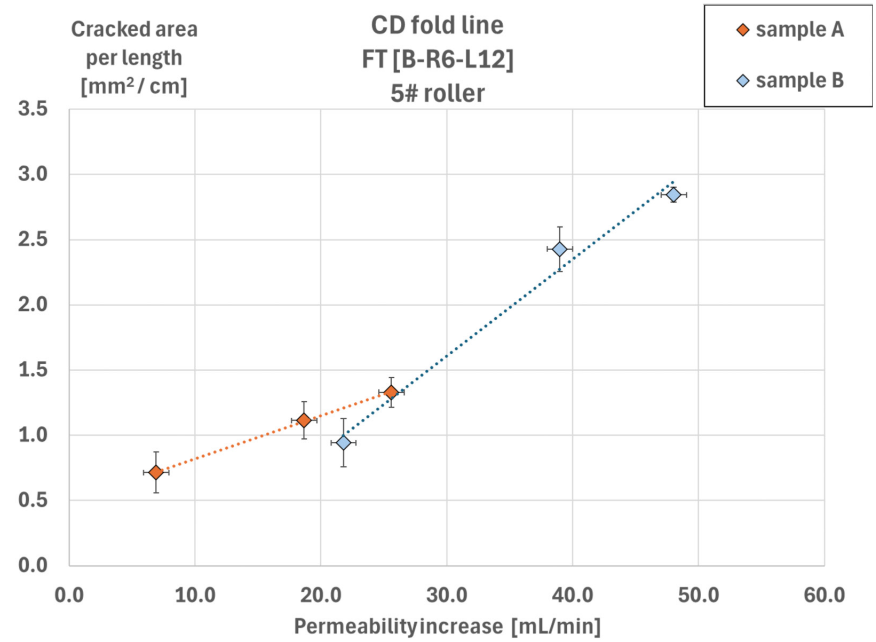
Figure 16 shows the cracked area determined from image analysis also increases with curvature. Sample A is approximately linear, while Sample B is clearly nonlinear. This trend agrees with the permeability increase measure-



15. Comparing CD and MD fold lines after folding [B-R6-L12] and compression with shims as noted. These CD fold line samples were used for cracked area image analysis in Fig. 16.



16. Cracked area per unit length from image analysis for CD fold line specimens in Fig. 15.



17. Comparison between cracked area and permeability increase.

ments, further highlighted by a correlation between cracked area and the permeability increase (**Fig. 17**). Note that while there may be a correlation within a sample, there does not appear to be a universal correlation, as the two samples fall on separate curves with substantially different intercepts and slopes (assuming a linear relation).

DISCUSSION

Proper folding to evaluate coating damage requires a well-defined and repeatable method. Use of a folding jig with specific tooling allows uniform folding along a straight line (Fig. 3 and Fig. 4). The amount of damage is driven by deformation at the fold tip, which in turn is determined by the folding geometry (as shown in Fig. 10 and Fig. 11) and the amount of compression after folding (as shown in Fig. 12 and Fig. 13). Folding geometry influences the point at which damage is first evident (damage initiation), as well as the maximum damage that occurs. A narrower clearance causes damage at a lower deflection and leads to a greater amount of damage; a narrower apex (blade) also caused a greater amount of damage, but did not have an obvious effect on the onset of damage. Both of these effects are believed to be due to a greater amount of curvature at the tip during the folding process; however, at this point there is not a reliable method for calculating curvature based on geometry, and it should be directly measured. With additional compression, using a shim provides a controlled and repeatable measurement that is not dependent on the applied force. The shim bears the load to avoid crushing of the tip and controls the amount of curvature. Compression without a shim is sensitive to the applied force and provides a worse case value (Fig. 14). For folding, a geometry with a 1 mm blade, 6 mm diameter rods, and a 12 mm spacing (minimum clearance of 6 mm) [B-R6-L12] is recommended. For compression, the use of a 2.3 kg (5 lb) roller with a shim of similar thickness to the sample is recommended.

For quantifying damage, the user should select a measurement that is practical and meaningful to their application. In this case, the permeability increase and the cracked area were used. The permeability increase was selected as a quick measurement since there were many conditions evaluated. This work does not intend to suggest that permeability increase is the best measure to quantify damage; this needs to be further investigated in relation to end use. Results from both measures show that damage is sensitive to the conditions of folding and compression. Within a sample, the measures are correlated with each other.

For future work, there are opportunities to:

- Isolate coating effects from substrate effects by further studying the effects of the substrate, including orientation, thickness, and properties.
- Clarify the effects of creasing by evaluating the effect of different creasing severity levels.
- Define operating windows by quantifying damage as a function of curvature.
- Better understand damage mechanisms by correlating damage response (including damage morphology) with driving factors (including directly measured curvature and in-plane deformation). Numerical modeling may be required.

- Validate transferability by comparing curvature and damage in different systems, including full-scale industrial operations.

The samples in this study had different coatings on different substrates of different thicknesses, without creasing. Thus, comparison of the samples and translation of the results is very limited. It is feasible that the sensitivity to folding and compression becomes less significant as the substrate becomes thinner; this is worth investigating. The orientation clearly has a significant effect, and the reasons should be further clarified. It is well known that one of the functions of creasing is to minimize surface damage during folding [3]. The effects of creasing severity [19] on coating damage should be evaluated using the folding and compression techniques described here.

Operating window is a term for describing damage as a function of deformation, particularly the initiation point, rate of growth, and maximum amount of damage. In other words, it describes at what deformation damage will start and how severe damage will get. This concept has been used for coatings and barriers on polymer substrates, for example, as shown in [20-22]. In principle, this can be used with package design, in combination with knowledge on how much deformation is expected and on how much damage can be tolerated. Measurements of the initiation point and growth of damage can be done by folding to different amounts of deflection and then evaluating specimens (as shown in Fig. 11) or direct measurement of strain and damage during the folding process, as described in [13]. Compression with shims of different thicknesses provides a measure of the increase in damage and the maximum amount of damage (Fig. 14 and Fig. 16). The goal is to open the operating window — to shift the damage initiation point to the right — to allow more deformation before damage starts and to reduce the amount of maximum damage.

Understanding damage mechanisms means knowledge of factors and relationships that cause damage, to the extent that damage can be controlled and predicted. This can be done by accurately characterizing damage (output) and comparing with the factors that are believed to influence damage (inputs). An important consideration is understanding that damage will be a balance between factors that cause damage with properties that resist damage [23]. For meaningful comparisons, numerical modeling may be required to handle the complexity of the system and response. The folding device shown in Fig. 2 allows visualization and quantification of deformation at the fold tip using DIC [13]. Further, the folding geometry is designed to be conducive for numerical modeling, such as described in [16]. Characterizing crack morphology gives guidance on how much is due to formation of new cracks vs. widening of existing cracks. All of this leads to further knowledge and insight into the key material properties and optimal structure, and ultimately what can be done to open up the operating window.

Potentially, transfer of results across different systems can be done using folding curvature, as presented in Fig. 14 and Fig. 15. However, this needs to be further evaluated and validated. Methods to calculate curvature during folding alone need to be further developed. In principle, clearly defined folding geometries make curvature calculations more direct; in reality, the formation of the fold tip and deflection of the paper make it more complicated (for instance, CD and MD fold lines on the same material in the same folding geometry show significantly different curvatures as measured by DIC [13]). Having said that, folding alone likely mimics a 90° fold during industrial converting. Determining curvature is more straightforward when using compression with a shim, as the structure is forced into a defined shape and the curvature can be directly calculated. Additional compression mimics 180° degree folds, such as during the industrial production of glued "flats," and the use of a shim close to the paper thickness should produce reasonable results.

CONCLUSIONS

Coating damage is sensitive to the folding geometry and amount of compression after folding. Defining the folding geometry and using precisely constructed devices allows reproducible results, as demonstrated here with two types of testers (DIC tester, fold tester). During compression, a shim should be used for controlled results; this allows calculation of the folding curvature. Compression without a shim provides a value of maximum damage. In this work, permeability increase and cracked area were used as measures of damage; users should use a measure that is practical and meaningful for their applications. **TJ**

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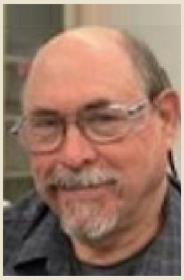
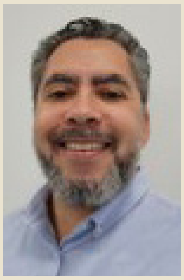


Mallory



Smith

The purpose of this study was to improve capabilities for evaluating coated paperboard during folding. This is experimental work that stemmed from our previous publication "Review of coating cracking and barrier integrity on paperboard substrates," *TAPPI J.* 21(11): 589(2022).

The most difficult aspect of this study was developing relatively simple methods and tooling to fold, compress, and evaluate the specimens. Through this study, we did gain further insight into effects of geometry on coating damage. Also, it was interesting to see how sensitive the coating damage is to the folding and compression conditions.

From this study, mills may see that more reproducible and transferable evaluation of coating damage is possible. In the future, further work is needed to quantify the onset of damage and maximum damage as measures of strength.

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