

Review of coating cracking and barrier integrity on paperboard substrates

JOEL C. PANEK AND PETER W. HART

ABSTRACT: Barrier packaging formats are major growth areas for the pulp and paper industry. It is technically challenging to maintain barrier properties during converting and end-use applications. Improved manufacturing capabilities and coating formulation knowledge will help maintain barrier integrity and enable growth of barrier products in challenging applications. These improvements will accelerate product development and commercialization, and allow faster response to product performance issues such as cracking.

The literature on coating cracking provides knowledge mostly on the effects of coating formulations and to a lesser extent on substrate effects. Despite a large number of publications dedicated to coating failures, the approach to improve coating cracking remains empirical, and the transferability between studies and to real life applications has not been well established. Model development that successfully predicts commercial performance is in its infancy. However, some of these simplified models do a fairly good job predicting experimental data. The current work reviews the state of understanding as regards coating and barrier cracking and highlights the need for more research on cracking and barrier integrity.

Application: Through this review, readers will learn more about coating cracking and the current state of knowledge on the topic. This can be used to guide product development and fundamental research.

Coating applications used to impart barrier properties to paperboard surfaces are a major growth area for the pulp and paper industry. As the desire to replace plastic with paper-based solutions accelerates, the need for more robust barrier applications will become paramount. Volume demand for functional and barrier coating applications in paper and board packaging reached almost 3 million metric tons globally in 2018, with a value of \$7.8 billion. The market is forecast to grow at a rate of 5.0% across the five years to 2024, pushing market value to almost \$11.0 billion and worldwide consumption to just under 4 million metric tons [1].

Barrier coatings tend to work extremely well when applied to a flat surface. Unfortunately, these coatings often experience damage and fracture during the bending, scoring, deep drawing, and press forming processes required to successfully convert a flat sheet into a functional package. Improved understanding of the fundamental aspects of barrier integrity will enable growth of barrier products in challenging applications, accelerate product development and launch, and allow faster response to product issues.

The current work on coating cracking attempts to clarify what is known about the mechanisms that cause damage to the barrier, to identify gaps in the existing knowledge, to propose potential driving mechanisms for crack initiation and propagation, and to recommend areas that require additional research.

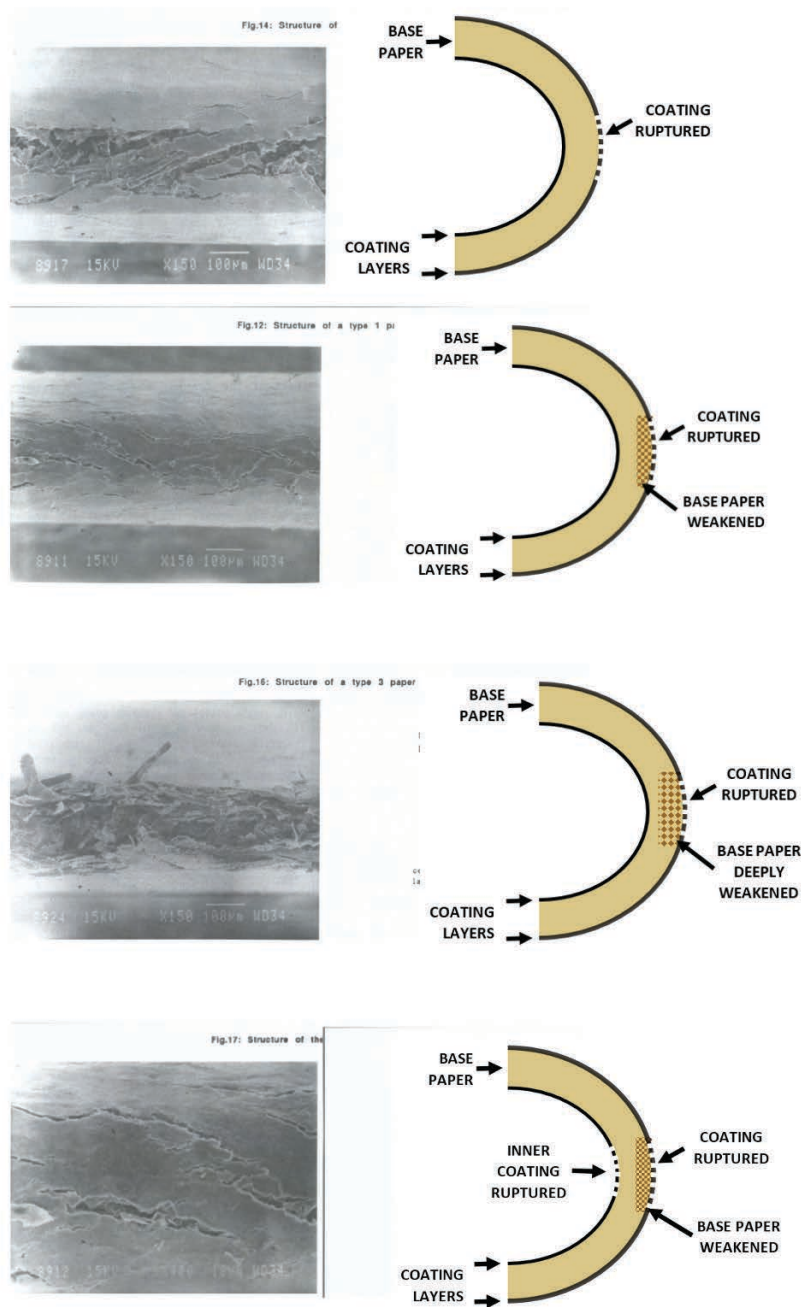
REVIEW OF THE LITERATURE

The literature on coating cracking primarily provides knowledge on the effects of coating formulations and to a lesser extent on substrate effects. Despite a large number of publications, the approach to improve coating cracking remains mostly empirical, and the transferability between studies to real-life applications has not been successfully established.

Early work — publication coatings

Much of the work in the early literature has been around the cracking of publication grades during folding. These give insight into deformation during the folding event, but these coating layers are quite different than barrier coatings due to the high pigment content. Early pioneering works by Colley [2,3] and by Jopson and Towers [4] on the cracking of lightweight magazine paper provide interesting examples. These studies do not provide significant insights into barrier applications due to the grades studied, the methods employed to quantify strength loss (i.e., damage), and a lack of mechanistic explanations. Guyot, Bacquet, and Schwob [5] describe different types of cracking behavior that depend on the relative properties of the coating and how these are related to the relative tensile properties of the coatings, which is conceptually useful. Detailed examples of these different types of cracking are shown in **Fig. 1**.

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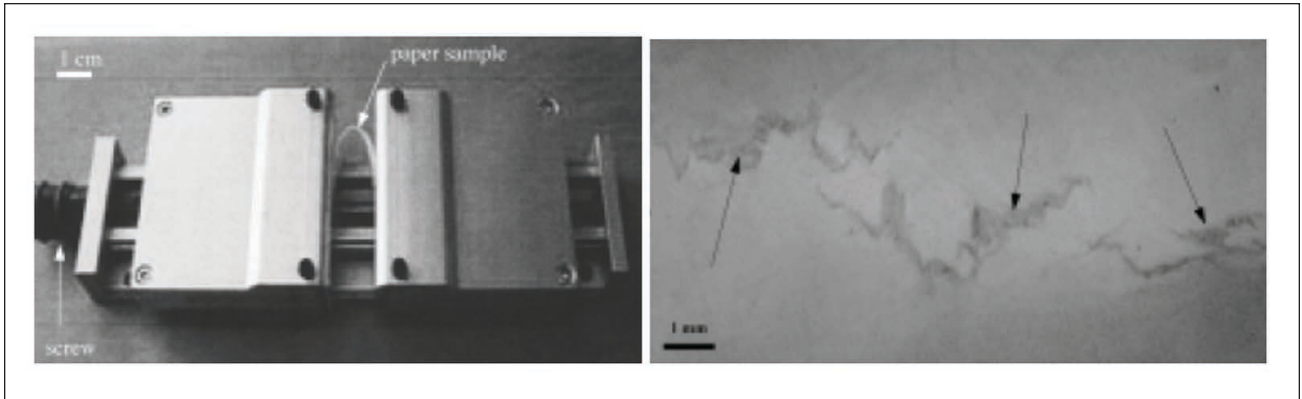
1. Four types of cracking behavior described by Guyot et al. [5]. For clarity, sketches on the right were redrawn based on the originals.

Fundamental studies

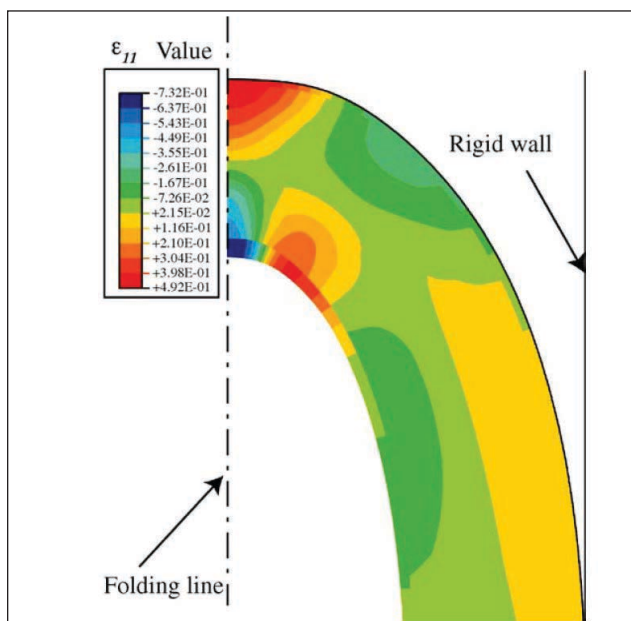
Barbier, Larsson, and Ostlund observed the initiation of cracks in the paper surface as paper was folded and compared this with numerical analysis [6-8]. They used an experimental jig to fold paper (**Fig. 2**), which allowed observation of crack initiation and deformation of the cross section. Their model (**Fig. 3** shows example output) had sound governing equations and reasonable outputs for the time (ca. 2005); however, it did not show any correlations

with experimental cracking results. Shortcomings in the model, such as out-of-plane deformation, damage mechanics, and plastic deformation, could potentially be overcome with modern commercial numerical codes.

Rätto et al. described an interesting method to evaluate cracking mechanisms employing a double-notched specimen deformed in tension [9]. A double-notched specimen was produced for isolated coating layers and coated paper strips and deformed in tension using a “micro material tes-



2. Experimental jig used and experimental cracking results from Barbier et al. [6].



3. Numerical modeling results from Barbier et al. [8].

ter.” A thermo camera and a high-speed camera were used to track crack initiation and propagation. The results were presented as crack area vs. time; time to crack initiation; and maximum propagation speed. This novel method has the potential to measure fracture energy and provide further insight into the failure mechanism.

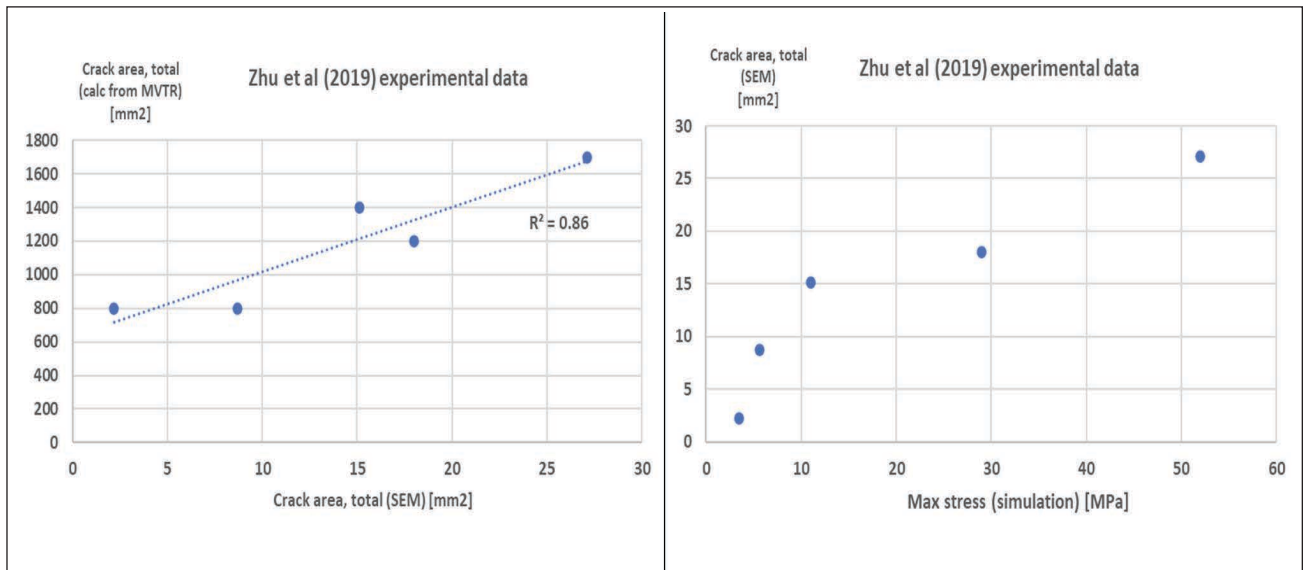
Alam et al. used modeling to provide a calculation of the balance between bending stiffness and cracking of paperboard [10-12]. While the proposed model attempts to incorporate parameters around the coating structure, clear connections with the experiments were lacking. The model is elaborate but not validated, so the accuracy of the strain distribution is unclear. Experimentally, the folding method is complex (first heating to 160°C and then folding in a Prufbau printability tester), which leads to dynamic conditions that are inherently difficult to model. Fold cracking is quantified as a tensile strength ratio of a folded vs. unfolded sample, rather than a direct measure of damage. There is no convincing experimental evidence that the proposed

ideal structure (a thin, stiff inner coating layer; a thick, low-stiffness middle coating; and a thin, low-stiffness outer coating) is indeed better.

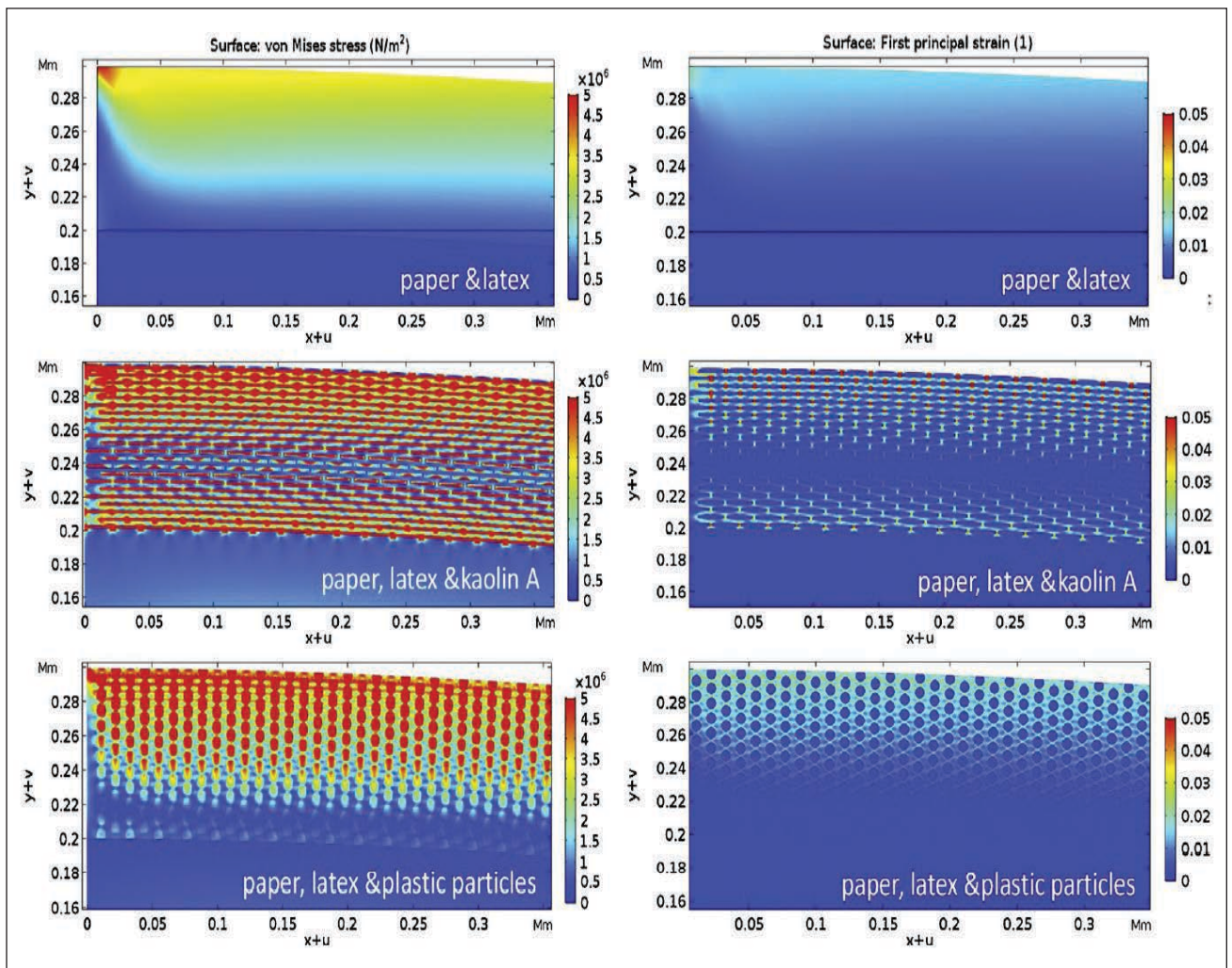
Zhu et al. [13-15] used a combination of experimental testing and modeling to investigate the effect of pigment type on damage in barrier coatings. The effects of pigment type on water (moisture) vapor transmission rate (WVTR) of folded samples was studied [13]. The WVTR was measured on paperboard with a grid of 6 fold lines. Scanning electron microscope (SEM) images of the folded regions were analyzed to characterize cracking. The crack area calculated from WVTR showed a good correlation with the crack area as measured by SEM, though the numbers were different by two orders of magnitude (**Fig. 4**). The authors point out that this difference is likely caused by limitations in detecting cracks with SEM. The deformation of a coating layer on a paper substrate during a two-point bend was simulated to clarify the effects of pigment shape and modulus on local stress and strain distributions. The coating layer was modeled as a matrix with evenly distributed particles that were either platey or spherical. The material properties were isotropic and linear elastic. The simulated structure was folded 5°, with the coated layer on the convex surface. Contour maps show the progression of stress and strain from the upper (coated) surface in contact with the clamp, to the lower surface away from the clamp (**Fig. 5**). The maximum stress and strain were higher for the higher modulus particles, which simulated kaolin. The measured crack area showed a monotonically increasing correlation with max stress, as determined from the simulation (**Fig. 4**).

In another work [14], coated samples were wrapped around rods with progressively smaller radii to determine the curvature at which cracking visually appears. This was combined with a theoretical simulation of a column under deflection to describe the strain state on the surface; the material model was similar to that used in [13]. Contour maps from the simulation show the strain in the coating layer at the fold line (**Fig. 6**). The simulation results show that higher strain concentrations are caused by a higher

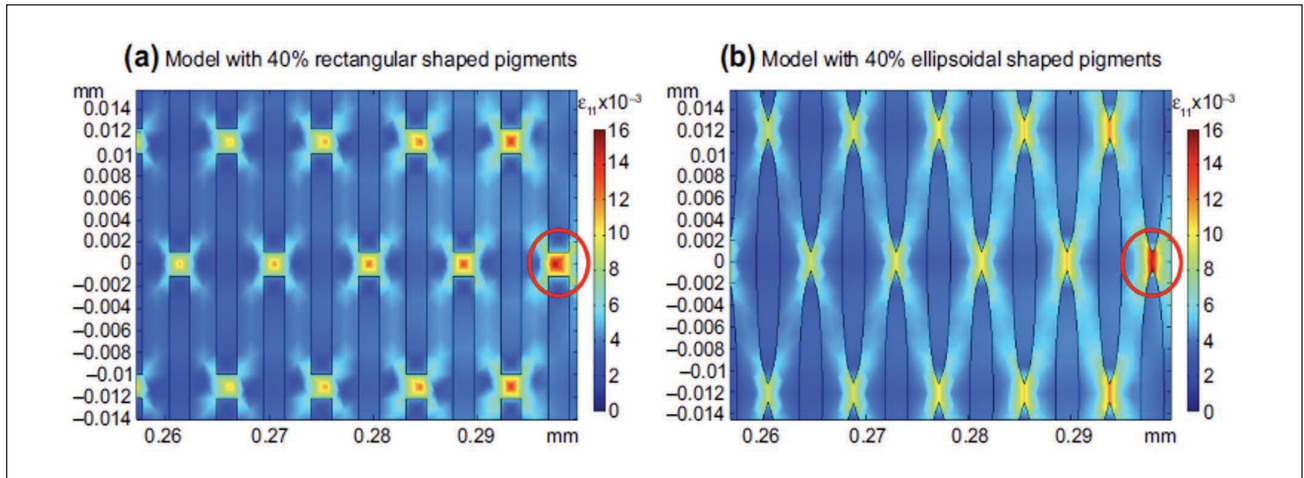
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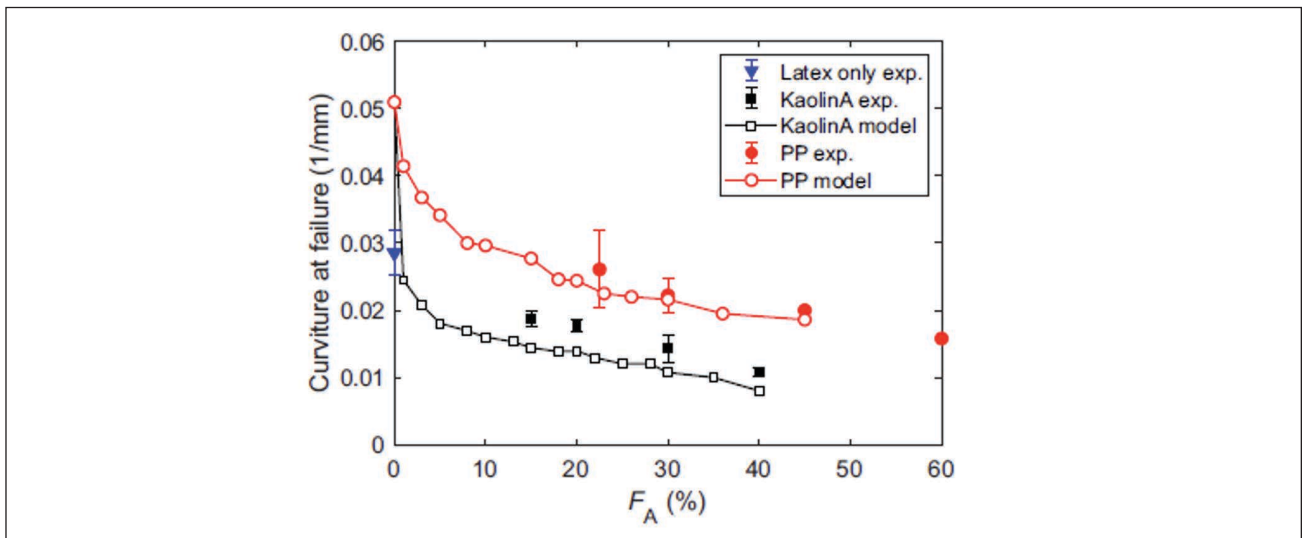
4. Crack area calculated from moisture (water) vapor transmission rate (MVTR) vs. measured crack area (left); and measured crack area vs. maximum stress from the simulation (right). Graphs produced from data in Zhu et al. [13]. (SEM = scanning electron microscopy.)



5. Stress and strain contour plots for simulations on the effect of particle size and modulus [13].



6. Strain contour at the midpoint of the column; the x-axis is the distance from the concave side [14].



7. Comparison between experimentally determined curvature and theoretically predicted failure curvature (F_A) [14]. (PP = plastic pigments.)

difference between particle modulus and matrix modulus and by high aspect ratio particles. Based on an assumed failure strain of 0.9% (failure strain of the latex), the model correctly predicted the trends due to the pigment type and concentration (**Fig. 7**). The absolute values differed by 15%–25%, which was attributed to the resolution of the experimental measurements and limitations of the model. The results from this body of work are encouraging; in spite of the simplicity of the model, the model correctly predicts that more particles and higher modulus particles will lead to more cracking.

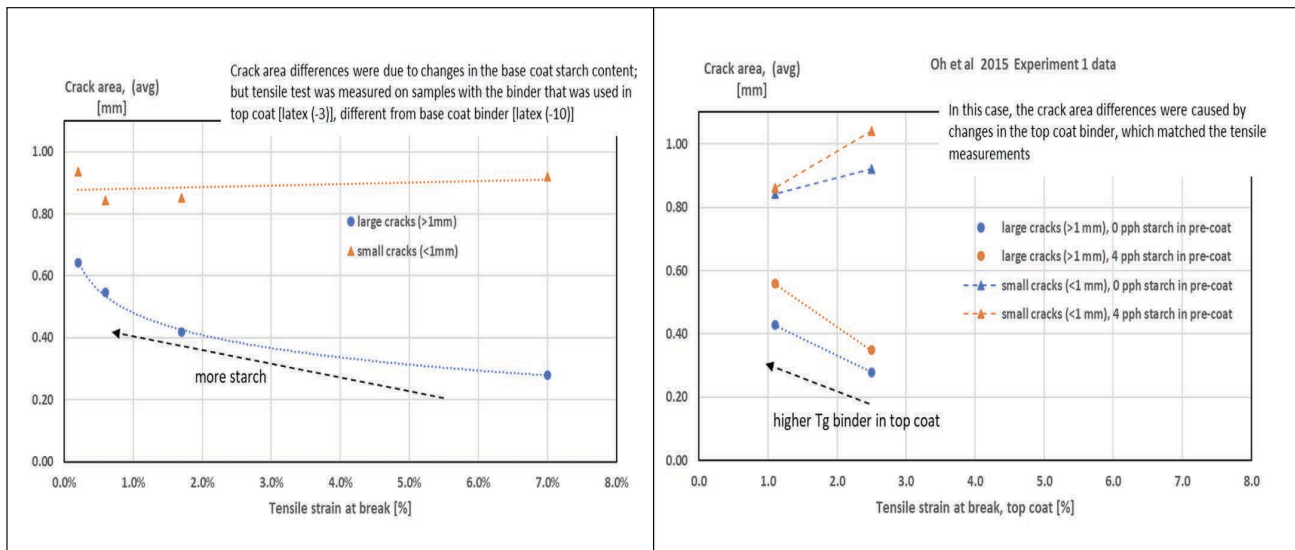
Coating formulation effects

Kim et al. demonstrated that a lower glass transition temperature (T_g) latex produced a lower amount of cracking and that printing can increase the amount and severity of cracking [16]. They suggest that lower T_g latex shows less cracking because it produces good film formability. They

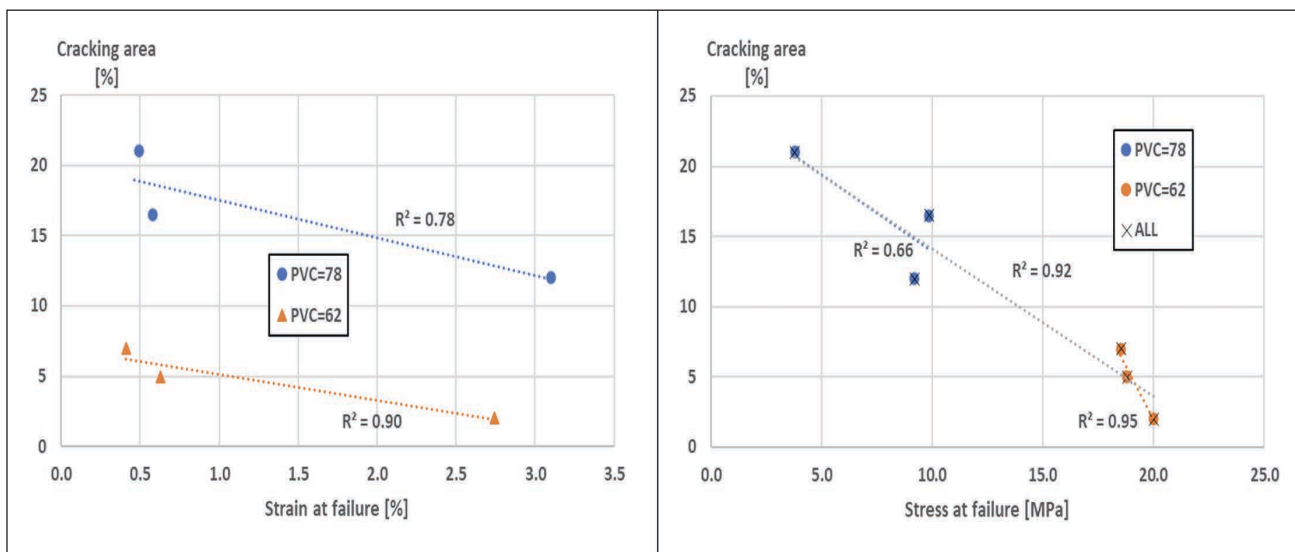
also state that ink and varnish make the coating more brittle, which directionally makes sense; however, these statements are not validated. Other researchers such as van Gilder [17] have identified that low T_g binder latex is known to have higher strain at failure than high T_g binder.

Oh et al. showed that either increased starch addition in the base coat or a higher T_g binder in the top coat caused an increase in the number of large cracks [18,19]. This work supports a strain-based failure criteria that suggests the changes that produce a lower strain to break result in increased crack areas. These researchers showed that the number of large cracks increases with a greater amount of starch in the pre (base)-coat, and they suggest that the pre-coat has a larger influence on cracks than the top coat. It was shown that the biggest driver of cracking was starch content in the base coat, but tensile data for those coatings were not presented. **Figure 8** could potentially be a very good demonstration of these effects, but it can only be as-

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8. Crack area vs. tensile strain at break for starch addition (left) and binder glass transition temperature, Tg (right). Graphs produced from data in Oh et al. [18].



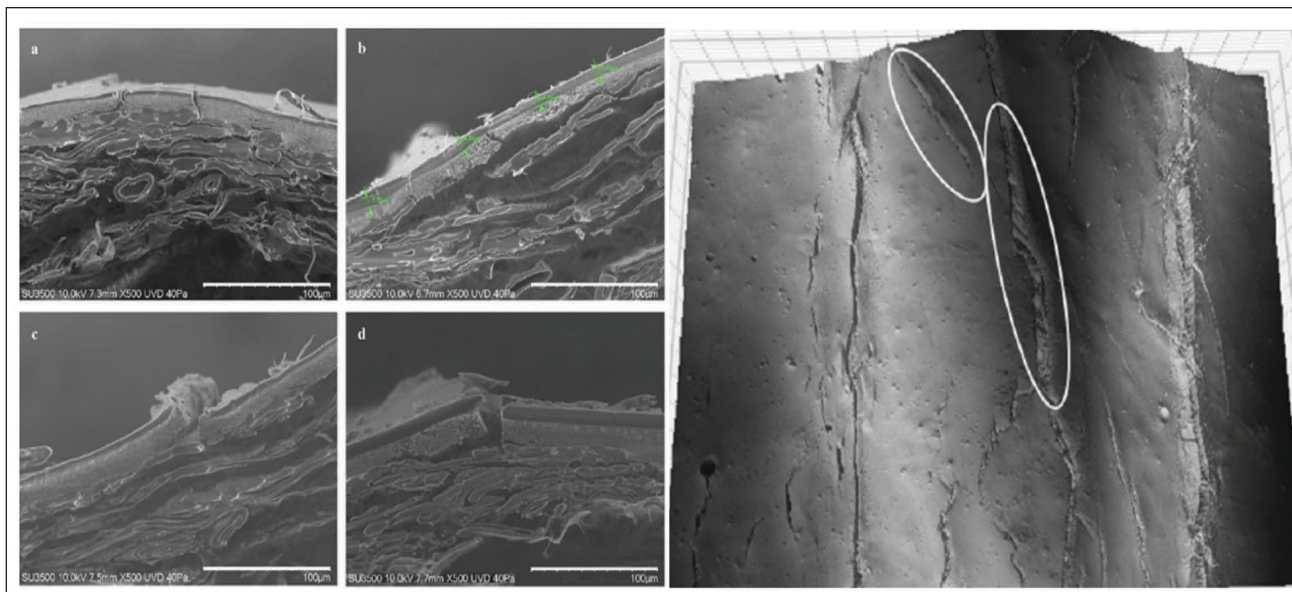
9. Cracking area vs. strain at failure (left) and stress at failure (right). Graphs produced from data reference [21]. (PVC = pigment volume concentration.)

sumed that the trend for more starch would be the same. Their comments on the effect of top coat vs. base coat are inconclusive, since different materials were used in each (base: low Tg coating with starch addition; top: higher Tg coatings with no starch addition).

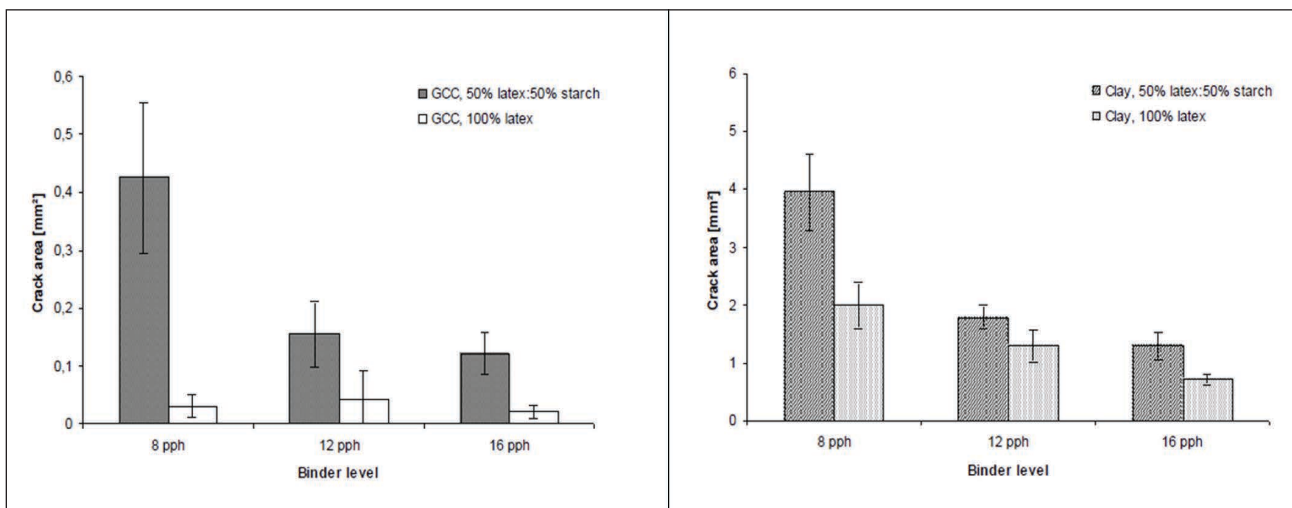
Following along the same path, Wang and Ding studied the effect of coating parameters on cracking [20]. Their experimental results show that high binder, more clay pigment, and low coating thickness are better for low fold cracking. They give broad directional explanations, but do not quantify the effects.

Najafi et al. showed that a higher amount of pigment volume concentration (PVC) and starch have a detrimental effect on cracking [21]. The research describes measuring

the strain at failure of a freestanding coating layer and how the pigment content correlates with crack area when folding. This work focused on high pigment content coatings. As such, the properties of the base sheet were not characterized, except for thickness and permeability. This work mostly agrees with Oh et al. [18] and states that strain at failure explains the effect of starch content, but that it fails to explain the latex effect. It is possible that stress at failure might provide a better explanation for both the effect of starch content and the latex effect (**Fig. 9**). Perhaps a fracture energy-based criterion would be better. Varney and Bousfield developed a model of the coating layer to simulate coating performance based on component properties [22,23]. This is an interesting approach, but so far, the pre-



10. Images of coating damage from [24].



11. Cracking results for ground calcium carbonate (GCC)-based coatings (left) and clay-based coatings (right), including effect of starch [25]. Note difference in the y-axis scale between the graphs.

dicted performance has not correlated well with experimental results.

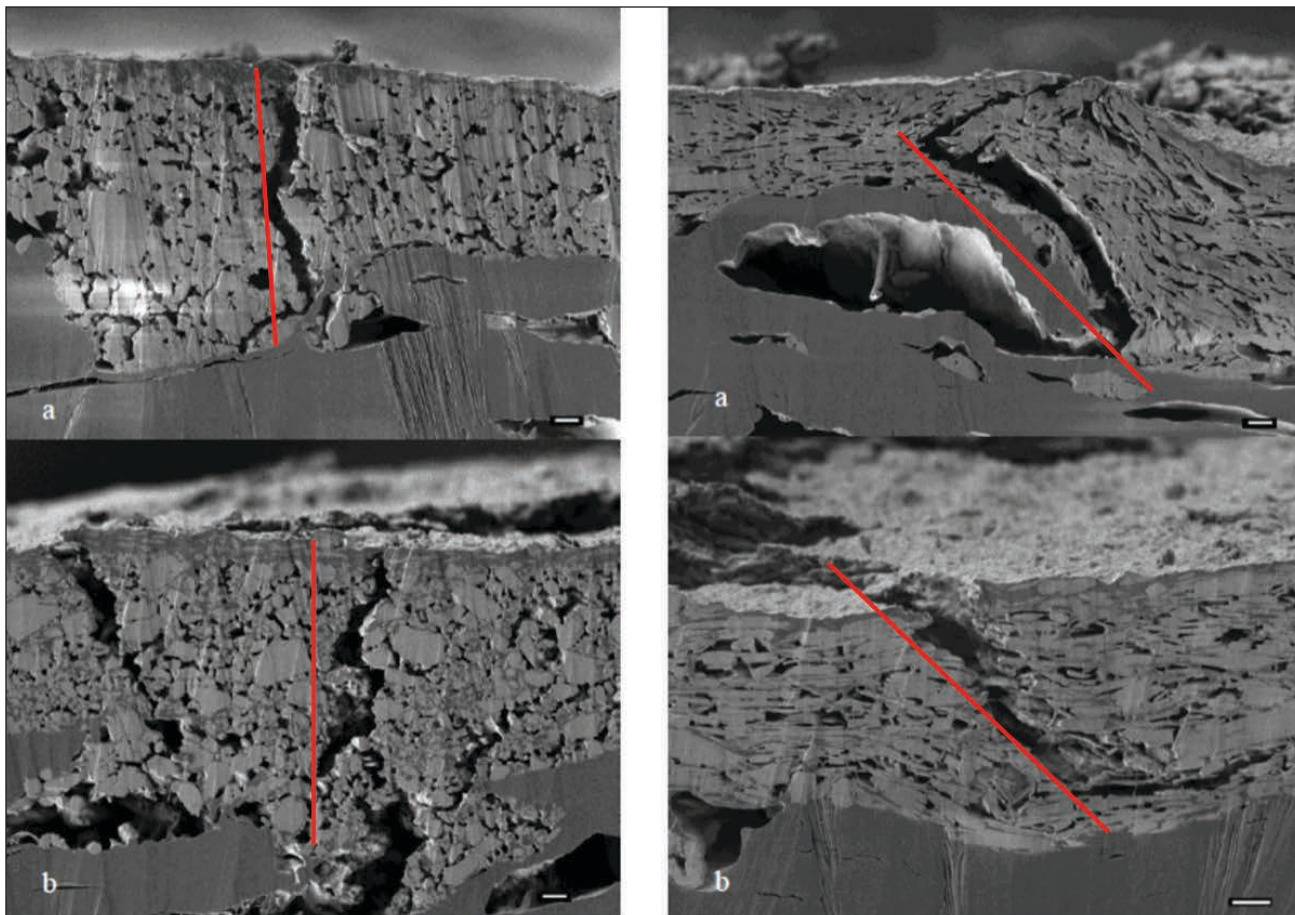
Javed et al. studied starch-based barrier coatings and the effects of plasticizer on cracking [24]. This work provides interesting images (e.g., **Fig. 10**), observations, and discussion; however, clear explanations of these findings are not established. There are good suggestions on what could be driving cracking, but they are difficult to quantify. The gaps are somewhat obvious: it is difficult to model the stresses and strains that develop in such a complex system; it is difficult to measure the correct properties of the coating layer, particularly out-of-plane properties; and it is difficult to quantify structural variation and defects that may affect fracture.

In a series of papers, Rättö and Hornatowska investi-

gated effects of coating composition on cracking [9,25-27], particularly differences in the amount of cracking and failure morphology between ground calcium carbonate (GCC) and clay pigments. Results are shown in **Fig. 11**. It is important to note that in the first and second articles [25,26], they only creased the samples but did not specify the creasing tooling that was used, whereas in the third article [27], they creased and folded the samples.

Higher binder, less starch, and GCC pigment are best for low cracking. The binder and starch effects corroborate what has been shown by other researchers. GCC-based coatings typically have a perpendicular crack, which is indicative of tensile failure, while cracks in clay-based coatings typically show a diagonal crack, which is indicative of out-of-plane tensile or shear failure (**Fig. 12**). This is con-

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12. Cross-section images of coating after failure for: a) GCC coatings (left) and b) clay coatings (right) from Ratto et al. [26]. Lines highlight fracture direction.

sistent with the assumed properties of the coatings; i.e., this particular clay produces a coating that is stronger in tension and weaker out-of-plane, due to its shape. The implications are that the potential for coating failure cannot be characterized by the in-plane tensile properties only. They suggest that failure occurs when stress exceeds the corresponding strength, which could be in-plane tension or out-of-plane shear, depending on the full structure and properties. They also look at the effect of the substrate on a large scale (board vs. copy paper). A theoretical framework for calculating failure is discussed, but it remained at a qualitative level. Measured properties of the different coatings were not included; rather, only qualitative trends were described.

Zhu et al. [13-15] presented work that showed high aspect ratio pigments are good for barrier properties until they are folded. For performance after folding, they recommend to minimize the amount of pigment. The use of thick base stock or coating layers increased the potential for cracking, as did high pigment loadings and high pigment aspect ratio. Modulus differences between latex and pigment also increased the likelihood of failure. Lower modulus, more deformable pigments tended to exhibit im-

proved failure resistance as compared with higher modulus, more rigid pigments.

Substrate effects

Sim et al. investigated the effect of mechanical properties of base paper on cracking [28]. They showed that the base paper can have an effect on fold cracking, though it remains unclear why it has an effect. The effect due to changing the softwood (SW) content, although significant, was relatively small; the cracking increased from 0.2% to 0.9% as the softwood content was increased from 0 to 100%. The mechanical properties showed substantial increases over that range, so it is hard to conclude that they are related when the cracking change was so small. The change in cracking may be due to physical structure, such as surface roughness, not the mechanical properties. The impact of refining (quantified as freeness) showed a larger effect on cracking. Highly refined (low freeness) hardwood (HW) combined with lightly refined (high freeness) softwood (SW) showed the highest amount of cracking. The SW freeness did not have a significant effect when combined with a mid-level freeness HW. There do not appear to be any clear correlations with the reported mechanical properties.

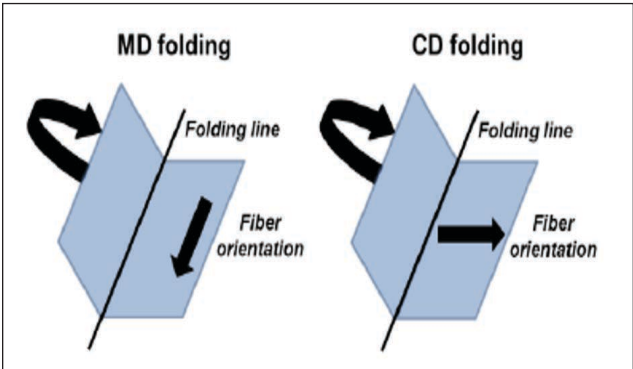
Conditions	Printing	Creasing	Folding, initial	Finishing	Reference #
Heat to 150°F	No	No	Manual	Cobb roller	2
Heat to 150°F	No	No	Mechanical device	Mechanical device	4
50% RH, room temp.	No	No	Mechanical device		6
50% RH, room temp.	No	Yes	Bending tester	Roller nip	29
Heat to 160°C	No	No	Prufbau tester		11
50% RH, room temp.	No	Die cutter	Calender nip		16
50% RH, room temp.	Laboratory printing	No	Mechanical device		18,19,28
50% RH, room temp.	IGT tester, cyan	Yes	Manual	Roller, 10 kg	9,24-27
50% RH, room temp.	Spray paint, black	No	Laboratory folding machine		21
50% RH, room temp.	IGT tester	No	IGT		20
50% RH, room temp.	None	None	Manual, 2 x 3 grid	4200 Pa pressure for 5 min	13

I. Sample prep for cracking evaluation (RH = relative humidity).

This study did not include bending stiffness or internal strength measures.

Kim et al. [16] and Oh et al. [19] both showed a difference in cracking degree due to the folding orientation (defined as the axis the sample is folded across, **Fig. 13**). A machine direction (MD) fold gives lower cracking than a cross direction (CD) fold and showed a different response to the binder properties. Cracking that occurs due to MD folding appears to be correlated with strain at break of the coating (as in the previous work), while cracking due to CD folding increases as strain at break goes up and appears to show a negative correlation with strength (**Fig. 14**). The authors' explanation for the difference in MD and CD response is interesting, but inconclusive. They claim that the discrepancy between MD and CD fold cracking is due to differences in curvature at the fold tip during folding that affects the point at which the cracks initiate. This suggests that the substrate properties play a significant part in the deformation and that the dynamics of crack growth are important.

The lowest grammage paper they used (110 g/m²) did not show a difference between MD and CD, did not show an effect due to pigment content and showed the lowest amount of cracking. This indicates that the strain on the outer surface is driving the cracking; the thicker the material, the greater the strain.

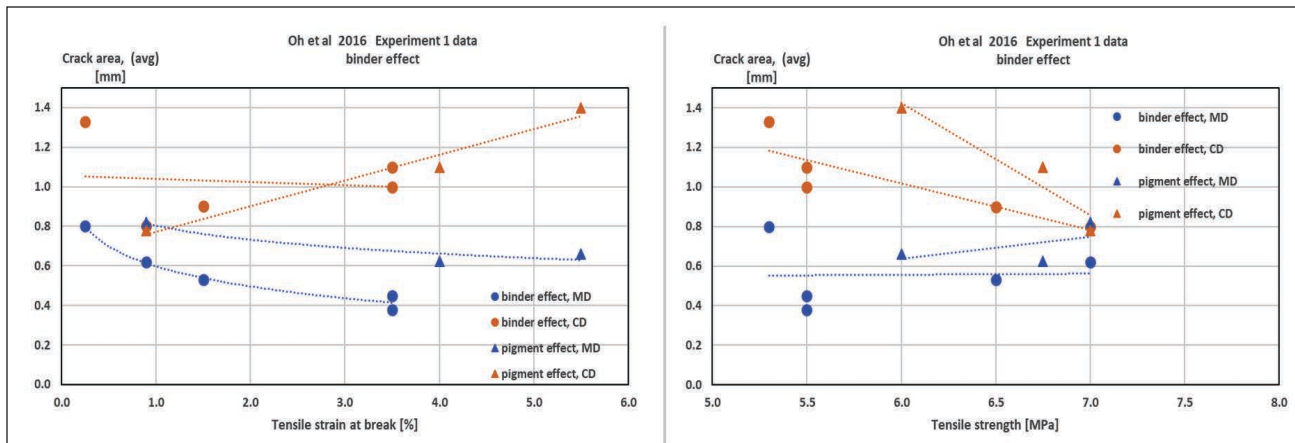


13. Definition of machine-direction (MD) and cross-direction (CD) folding, from Oh et al. [19].

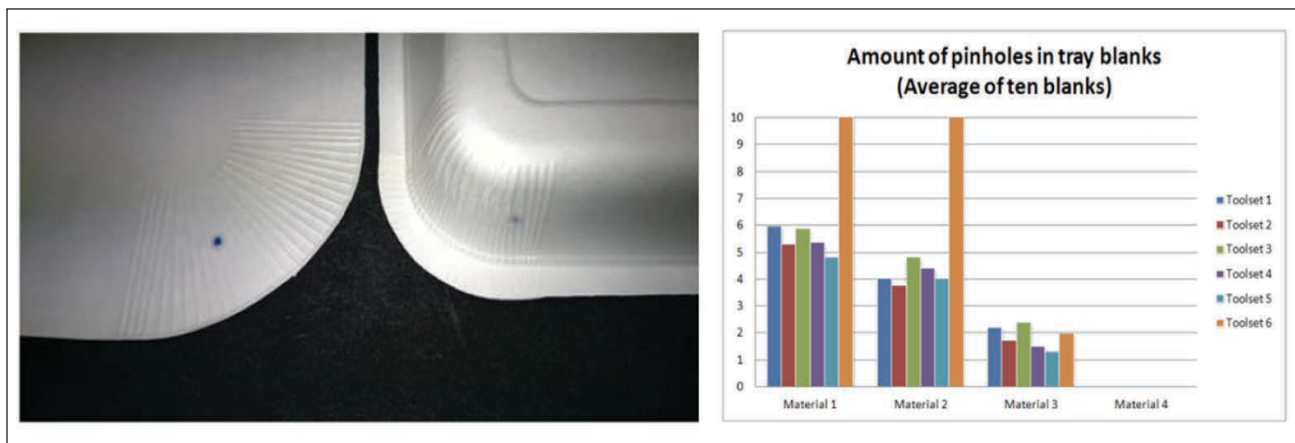
Creasing effects

Articles related to crease cracking include Nagasawa [29], who investigated damage to an aluminum layer; Tanninen [30], who investigated the effect of creasing tooling on a barrier coating during die cutting and tray forming; and the work by Panek [31] and Mirzaei [32], who investigated reverse-side cracking of the fiber surface.

Nagasawa et al. studied cracking of aluminum foil (as opposed to standard coating) on paper [29] and included the effects of creasing depth on the magnitude of failure. Nagasawa's work related creasing tooling and creasing



14. Crack area vs. strain at break (left) and crack area vs. strength (right). Graphs produced from [19].



15. Analysis of pinholes in trays [30].

depth to a creasing shear strain and showed that cracking increased above a creasing shear strain (calculated). They suggest that the aluminum foil strain at break was important for failure, but did not conclusively validate this.

Tanninen studied effects of creasing tooling on cracking that occurs during die cutting and tray press forming of biopolymer dispersion-coated paperboards [30]. This work shows that damage is done in the die cutting/creasing process, and a range of tooling did not have a significant effect beyond a “worn toolset.” **Figure 15** shows these details. Tanninen’s comments suggest that coating cracking is sensitive to the creasing depth, but low enough pressure/creasing depth apparently could not be obtained in their studies to experimentally validate this assumption.

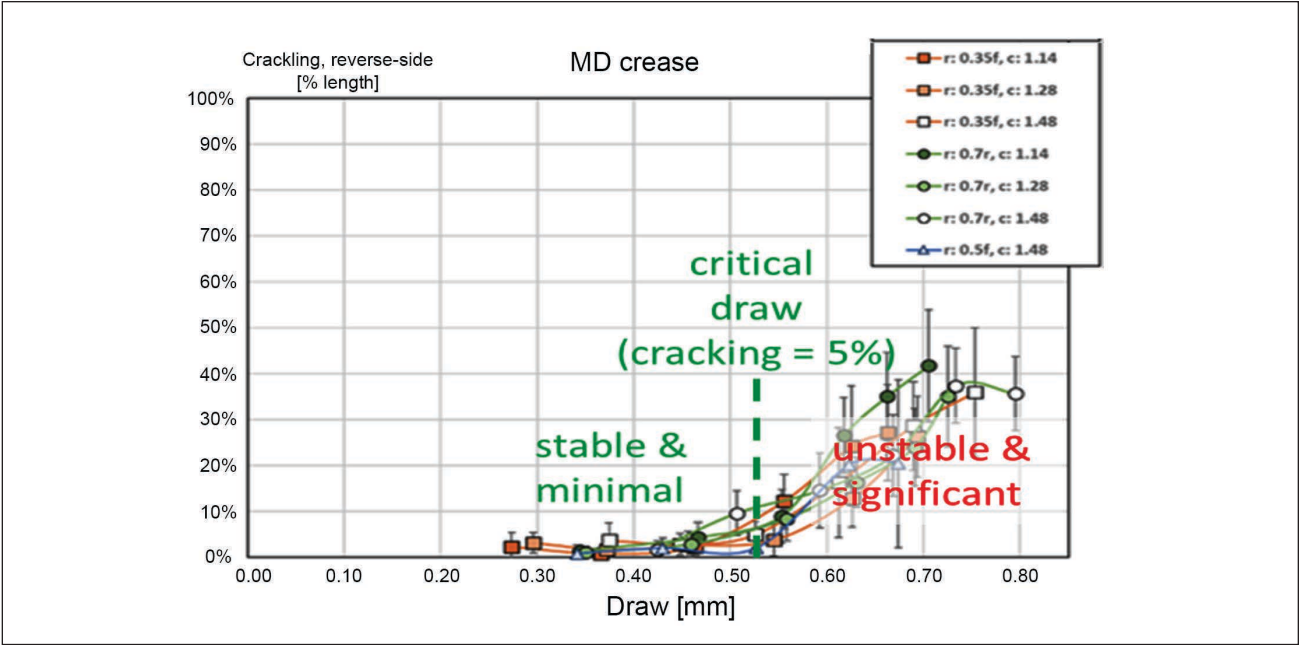
Panek et al. [31] derived a creasing draw (draw is the amount or depth of substrate drawn into the creasing tool) to describe the severity of creasing, and demonstrated that reverse-side (fiber) cracking would increase exponentially beyond a critical creasing draw. They suggest an operating window concept, such that the creasing conditions should remain to the left of the critical draw to minimize cracking. **Figure 16** details this operating window concept.

Mirzaei et al. [32] used the concept that the material

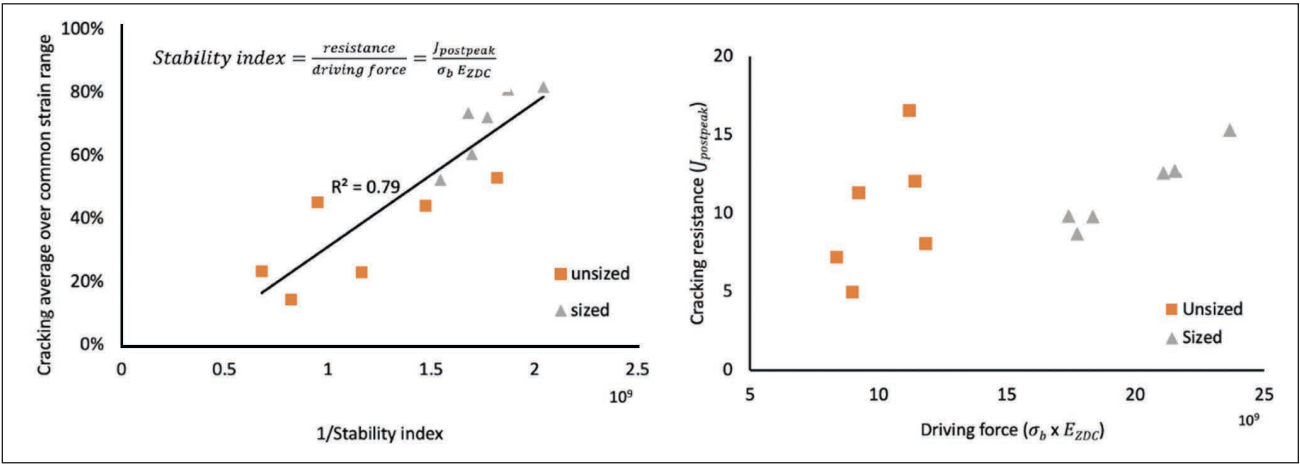
properties will affect both the cracking resistance (post-peak energy) and the driving force for cracking (bending force, z-direction [ZD] compressive modulus) to propose a stability index as a ratio of the cracking resistance divided by the driving force. They demonstrated a correlation between cracking degree and the stability index. As an interesting point, they demonstrated that the addition of surface (size press) starch had a larger effect on increasing the driving force, but had no effect on the cracking resistance. **Figure 17** shows the impact of size press-applied surface starch and demonstrates the stability index.

DISCUSSION

The essence of barrier integrity is to control the onset and severity of damage to coatings during converting and end use. The outcome is practical knowledge to expand the range of materials (such as bio-based) and package configurations for paperboard-based packaging in barrier applications. In this case, we are addressing damage to coated paperboard under two-dimensional folding. The failure mechanism that coating will crack when its strength is exceeded by a driving force is likely true. But application of this concept towards coating cracking, and by extension,



16. Critical draw concept from Panek et al. [31].



17. Stability index proposed by Mirzaei et al. [32], and the effect of the surface starch (sized vs. unsized) on the cracking resistance and driving force for cracking (bending force, z-direction (ZD) compressive modulus).

to barrier damage remains at a qualitative level. It is uncertain which property best describes the strength and is unclear how to best describe the driving force. Three areas that are integral for advancement in understanding cracking are: a) testing and analysis methods; b) material properties and structure; and c) modeling and simulation.

Testing and analysis

Testing and analysis should be standardized for reliable results and for transferability. Tests should be well-defined, precise, reproducible, and repeatable. Deformation, forces, and damage should be quantified to an extent that is feasible. Analysis should present the results in a format that is understandable, meaningful, and transferable.

Some type of folding has been used for all the coating

cracking tests described here, which is summarized in **Table I**. Folding is simple to do and typically causes cracks. However, methods vary and the reproducibility across the methods is unknown. Sample preparation methods, sample orientation, and mechanics of folding should be described well enough for somebody to repeat the work and understand what may cause differences.

Folding can be complete or progressive. Complete folding is deforming the sample across a line to the point of surface-to-surface contact at 180°. This is commonly done with the belief that this represents an extreme condition that produces a maximum level of damage. In practical applications, it is assumed that the actual damage may be less, but it is unlikely to be worse. This type of test should be repeatable and reproducible, provided that the method

Characteristic	Apparatus	Metric	Reference #
Loss in strength	Tensile or burst test	Loss in strength	2,4,11
Cracks	Microscope	Strain (calculated) at which cracks first appear	6
Cracks	Microscope	Width, frequency	29
Cracks	Microscope	Cracked area (no details)	16
Cracks	Scanner, image analysis	Cracked area (includes details)	9,18-21,25-28
Cracks	High speed camera	Cracked area	9
Cracks	Microscope (optical, SEM); surface profiles	Cracked area, frequency	24
Cracks	Visual ranking	Cracking degree	20,24
Cracks	SEM	Area, number, width	13
Barrier	OTR	Difference	23
Barrier	WVTR	Absolute values	13
SEM = scanning electron microscope; OTR = oxygen transmission rate; WVTR = water vapor transmission rate.			

II. Quantification of crack at fold.

is described well and accurately followed. Shortcomings are that it is difficult to know exactly what is happening, which hinders analysis and modeling.

Progressive folding involves evaluating samples at intermediate levels of folding or continuously monitoring the material directly during folding. This can be used to evaluate the initiation and progression of damage by monitoring for damage as deformation progresses. The point of damage initiation can be used to describe the amount of deformation that the system can withstand before barrier performance is compromised. Progressive folding is best done using a bend test with defined geometry and constraints so that the deformation is quantifiable and the stress and strain states can be approximated. Folding to intermediate levels can be to prescribed angles (such as 30° or 90°) or by folding around rods of different diameters [14]. While this approach may be tedious and limited in resolution, depending on the number of levels, it still gives a good approximation as to when damage first occurs and insight into how to control it. Continuous monitoring can be done with a proper video camera and experimental setup. Digital image correlation (DIC) is ideal for this approach. However, this requires equipment and method development.

Quantification of the amount of damage is necessary for analysis. Methods used in the literature are summarized in **Table II**. Damage can be quantified as a characteristic of the physical structure, such as crack density and area, or it can be quantified as differences in barrier performance. Accurate measurement of the physical structure can be challenging. The majority of tests evaluate visual

damage to the coating by using magnification (microscope, scanner) to amplify the presence of cracks. The use of ink to provide contrast and scanning to provide accurate measures is useful, but it is important to calibrate the measurements, document limitations in precision, and understand effects due to image analysis settings. Scanning electron microscopy is useful, but it requires the correct equipment and can be tedious. Damage generally means cracks in the coating; however, damage can occur and affect barrier performance without being visually obvious, even under magnification. Damage to coatings (particularly barrier coatings) should be evaluated with relevant and sensitive tests for which the coatings were designed. These tests include oxygen transmission rate (OTR), moisture vapor transmission rate (MVTR), porosity, and staining. Characterization of crack morphology is useful to understand effects in more detail and provide insight into the mechanisms that cause damage. More detailed analysis of crack morphology may be needed for accurate correlations with barrier performance.

Material properties and structure

Material properties and structure should be more thoroughly characterized to allow more accurate analysis and identification of secondary effects. This includes identifying all relevant characteristics and determining these at an appropriate level. Even though coating formulations have clear effects on cracking, key properties that affect failure and mechanisms that drive failure have not been clearly established. Relationships between coating cracking and material properties have been shown in certain cases, but

the transferability to other cases is inconclusive. Trends can be different, depending on the size scale of the cracks. The following comments are on characteristics that influence cracking, recognizing that much still needs validation.

Generally, coatings should be tough and uniform. Toughness is likely a better descriptor, as it encompasses both strength and strain and can be quantified with a fracture energy. The coating should be tough in all modes, including out of plane tensile and shear. Uniformity in the structure will help to minimize stress concentrations, which will lead to failure. Non-uniformity can originate from variations in the physical structure and from differences in properties of the coating components. The smoothness of the substrate will affect uniformity of the coating and the presence of stress concentrations. Intrusion of fibers into the coating (e.g., raised fibers) can be detrimental.

The substrate should be relatively weak out-of-plane and locally delaminate during folding, which reduces the surface strain. The best measurements of out-of-plane properties are not established, but documentation of relevant measurements such as ZD tensile (ZDT), Scott bond, and shortspan compression is helpful. The optimum in-plane properties are unclear. There is reason to believe that the substrate should be tougher in-plane than the coating to provide cohesive support and minimize the amount of stress on the coating. At the same time, there is reason to believe that the substrate should have a relatively low modulus to minimize the stress during folding. The balance between maximizing strength while minimizing driving forces is complex and dependent on the system.

Accurate measurement of coated paperboard is challenging and has many limitations. It is relatively non-uniform and has a discrete (non-continuous) structure as compared with the scale of damage. Coating layers are a composite that have a variable interface with a fibrous structure, which makes it difficult to characterize. At high levels of deformation, the material typically shows non-linear and ductile mechanical behavior, and damage is occurring to the substrate during deformation. A coated layer that is deformed within a span of millimeters (as during folding) does not necessarily have the same properties that are measured as an isolated coating with a standard tensile test.

Having described these limitations, it is vital to continue developing characterization methods. It is important to understand shortcomings and validate the transferability of properties across different configurations. At the same time, sound approximations of properties by indirect measurement, calculation, or assumption are useful in advancing knowledge.

Modeling and simulation

Modeling and simulation can be a powerful tool to explain effects, predict results, and guide further work. While the benefits are enticing, there is still a long way to go in mod-

eling coating cracking. Folding to small radii of curvature is an obvious cause of damage, but it is inherently difficult to model. It is a composite system under high deformation, where complex stress states, non-linear effects, and damage become more prevalent. Multiple modes can drive the initiation and propagation of damage. The relative properties of the materials, their physical structure, and the extent of deformation all can play a role. There are many challenges, but advances in knowledge of material behavior and computational methods will bring us closer to solutions, one step at a time. Recent work has shown the usefulness of relatively simple models to correlate pigment characteristics with experimental results [13,14].

Models should be fundamentally sound, validated, and with mechanisms that relate damage with driving factors. It should be on the right level: detailed enough to capture essentials, but not too complex to require excessive parameters and a high computational cost. The ability to accurately describe an entire physical system should not be an initial requirement. At a minimum, a model needs to provide a better description of the region of interest. A model can be effectively employed as a virtual microscope, providing focus on specific aspects of cracking damage.

CONCLUDING REMARKS

Published literature on coating cracking is useful to understand, but it is still limited in terms of what is directly beneficial for commercial applications. There is qualitative knowledge on what affects cracking, but there are still gaps in quantifying effects and unknowns in fundamentally understanding why. Further advances in standardizing testing, measuring key properties, and modeling the mechanisms will be important to develop a more comprehensive set of knowledge and tools available to predict coating and barrier damage. **TJ**

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ABOUT THE AUTHORS

We studied this topic for the purpose of improving our ability to enhance performance of barrier coated packages in demanding applications. The intent of this review was to clarify what has been done in previous research in order to give guidance on what research should be done in the future.

The most challenging aspect of this review was to distill learnings from the research of others and combine them with our own beliefs and observations to the point we could propose what we believe to be an effective route forward. Coating cracking is an area where it is fairly straightforward to get some sort of results, but difficult to quantify what is occurring on a local level. Due to this, it is important to distinguish what are validated conclusions from what is speculation.

This study emphasizes the value in taking the time to properly read and understand relevant literature. There are conclusions and beliefs that are not truly supported; at the same time, there are observations and results that are overlooked or downplayed. It is important to take a step backward and distinguish what is valid, where there are gaps, and what effective paths can close these gaps.

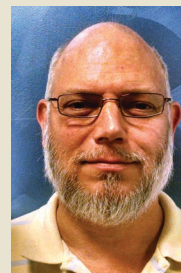
Much of previous work on this topic has been hindered by lack of knowledge on what is occurring at a local level. The tools and knowledge available to us

as a community have developed so that we can measure deformation on a small scale and more accurately model stresses and strains. Coupled with implementing defined and repeatable methods, we are better positioned to advance knowledge in this area.

With further study and advancement of knowledge and evaluation methods in this area, mills can benefit through more effective product development. We hope this study encourages and provides guidance for more fundamental research on this topic. Internally, we are completing research on setting up digital image correlation (DIC) to measure surface deformation during folding and are developing standard methods to fold samples.



Panek



Hart

Panek is senior principal R&D scientist and Hart is director, Fiber Technology and Innovation, at WestRock in Richmond, VA, USA. Email Panek at joel.panek@westrock.com.

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