

Creasing severity and reverse-side cracking

JOEL C. PANEK, SWAN D. SMITH, AND DOUGLAS W. COFFIN

ABSTRACT: Crease cracking can be detrimental to the functionality and appearance of paperboard-based packaging. The effect of creasing severity on the degree of reverse-side crease cracking (bead-side of the crease) of paperboard was investigated. Samples were creased with a range of rule and channel geometries, and the cracking degree was quantified as the percent of cracked length relative to the total length of the crease. The cracking degree was typically below 5% at low crease penetration depths, but was exponentially higher beyond a critical penetration depth. A rule and channel combination with a wider clearance shifted the critical depth to larger values.

The creasing severity parameter, termed the creasing draw, converged the cracking degree data from different rule and channel combinations to a single curve. The creasing draw was derived from the same analytical expressions as the transverse shear strain and quantifies the length of paper that is drawn into the channel during creasing. The critical draw is defined as the draw at which cracking becomes greater than 5%, which corresponds with the point at which cracking becomes exponential. The critical draw is a material/system parameter that defines the level below which cracking is minimal.

Application: For mills, the creasing operating window plot gives guidance on the tooling and penetration depth combination that will maintain creasing at an acceptable level. Paperboard converters can then choose a penetration depth that is deep enough to give an acceptable relative crease strength (RCS), without going too deep to produce cracking.

One objective of creasing paperboard is to reach a target folding strength (e.g., relative crease strength, springback, % kill, etc.) without damaging the surface of the paper. To facilitate this in production, creasing guidelines suggest the best tooling geometry to use for a given paper grade. The purpose of our research is to provide a stronger theoretical framework for describing creasing severity that will enable calculation of the optimal tooling for an application.

A more thorough discussion of the literature pertaining to creasing and folding was recently given by Coffin and Nygård [1]. Here, we focus on pertinent concepts regarding cracking. Crease cracking generally refers to visible damage on the outer surface of the creased region. Cracks may become apparent during any point of converting and end use. They may be visible prior to folding, but they often appear or become worse during the folding. In the present study, we investigated the cracks that formed on the bead side of a crease, when folded 180° opposite from the bead of the crease. The cracking was evaluated on the reverse side of a one-sided premium coated paperboard.

In our previous work [2], we focused on quantifying the transverse shear strain that occurred during creasing and demonstrated how the relative crease strength (RCS) upon folding correlated with this value. The transverse shear strain to achieve a target RCS could be determined with one set of creasing tools, and then transferred to other tooling combinations. In this current work, we demonstrate how a derived expression for the change in length (draw) corre-

lates to the amount of reverse side cracking that occurs in a double fold. Similarly, the critical draw determined from one set of tooling could be transferred to other tooling combinations. Thus, an operating window was constructed to describe a range of tooling and penetration depth combinations that gave acceptable creasing/folding performance.

The concept of shear angle and draw length date back to the original 1939 work of Halladay and Ulm [3] and later re-derived by Emslie and Brenneman [4] in 1967. Their equations do not adequately account for the shape of tooling, nor the clearance between the rule and the channel. Our work presented in [2] and here provide kinematically admissible descriptions of the creasing operation.

There have been very few articles that address the effect of creasing conditions on crease cracking. Halladay and Ulm [3] simply stated that the creasing operation needs to reach a minimum transverse shear angle (they termed angle of break) to achieve a good fold, but if the sheet cannot handle the draw, cracking is the likely outcome. They suggested that with some boards, one cannot achieve the minimum break angle without cracking.

Cavlin, Dunder, and Edholm [5] previously described an approach to define a range of rule heights that gave acceptable creasing properties. They used a set of inclined rules to crease samples over a range of penetration depths and then characterized the minimum rule height (penetration depth) that produced a low enough crease strength and the maximum rule height (penetration depth) that did not cause cracking. This concept of an operating window was

adopted in the present study. Whereas the previous results were limited to the specific tooling combinations tested, a more general approach is presented here. In this case [5], cracking was qualitatively described as with or without cracking. Cavlin [6] previously had described an approach to quantify cracking as the ratio of cracked length to total length; however, that work focused on material property effects, not tooling effects.

Nagasawa et al. [7] investigated cracking of aluminum foil coated paperboard. For that study, the foil was on the rule/valley side of the crease; the crack magnitude was characterized by the width of the crack in the aluminum foil or by the percentage of samples (out of 5) that had cracks in the foil. They increased the penetration depth for a single set of tooling and used the shear strain to quantify the creasing severity. The magnitude of cracking decreased as the penetration depth increased; this was due to stress relief by causing the material to buckle inwards. They characterized cracking for a single set of tooling but did not demonstrate whether these results were transferable to other combinations.

THEORY

A model to describe ideal creasing deformation was previously presented [2]. Using the parameters in **Table I** and geometry as defined in **Fig. 1**, the dimensionless parameters for displacement, clearance, and angle are defined as:

$$\text{Crease displacement: } \kappa = \frac{z}{r_c + r_b + t} \quad (1)$$

$$\text{Crease clearance: } \lambda = \frac{(c-b-2t)}{2(r_c + r_b + t)} \quad (2)$$

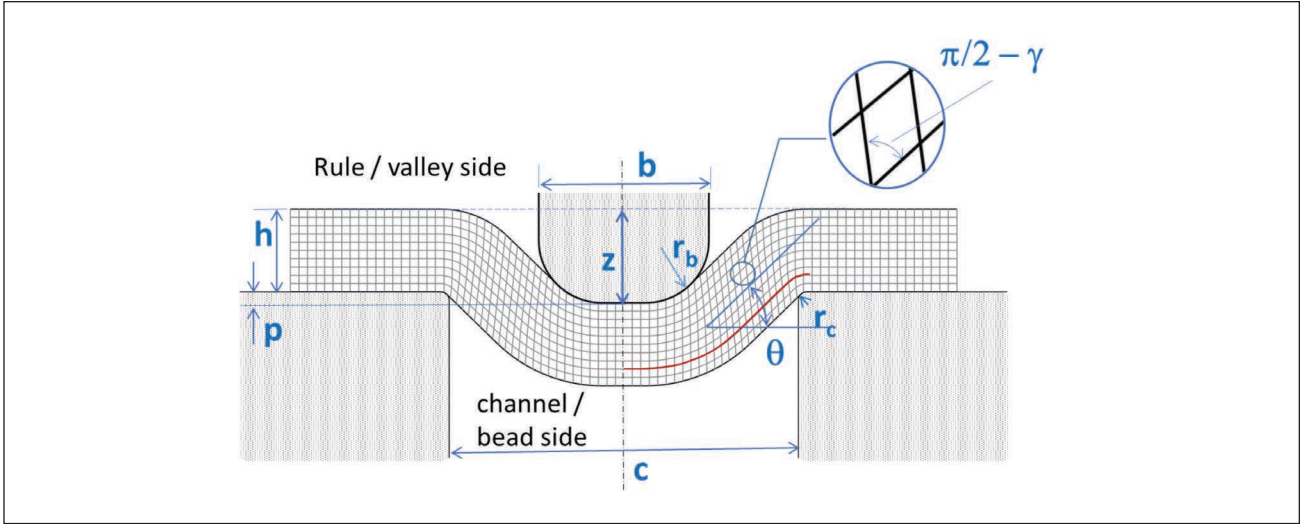
$$\text{Crease angle: } \theta = \tan^{-1} \left(\frac{\sqrt{(1-\kappa)^2 + \lambda(2+\lambda)} - (1-\kappa)(1+\lambda)}{\lambda(2+\lambda)} \right) \quad (3)$$

Assuming that the thickness remains constant and that elongation in the plane is negligible, the transverse shear strain is calculated as:

$$\gamma = \tan^{-1}(\theta) \quad (4)$$

Parameter	Name	Notes
t	Material thickness	
b	Rule width	
r_b	Rule radius	Flat tip, when $r_b=0.05$ Rounded-tip, when $r_b=0.35$
c	Channel width	
r_c	Channel radius	
z	Crease depth	Position of rule tip relative to top surface of the material $z = 0$ when rule tip is level with top of material; positive when tip extends into the material
p	Penetration depth	Position of rule tip relative to top surface of the channel $p = 0$ when rule tip is level with top of the channel; positive when tip extends into the channel $p = z - t$
CL	Nominal clearance	Standard equation for gap between channel and rule $CL = c - b - 2*t$
D	Draw length	Increase in length of material formed into the crease, Eq. 11
κ	Crease displacement	Dimensionless displacement, Eq. 1
λ	Crease clearance	Dimensionless clearance, Eq. 2
θ	Crease angle	Eq. 3
γ	Transverse shear strain	Eq. 4
β	Crease draw	Dimensionless increase in length, Eq. 5
ε	Crease strain	Strain based on the draw and the channel width, Eq. 12.

I. Creasing parameters (mm).



1. Geometry for creasing model.

When the clearance is zero ($\lambda=0$), the crease angle reduces to $\theta = \tan^{-1} \left(\frac{\kappa(2-\kappa)}{2(1-\kappa)} \right)$. Here, we are also interested in the crease draw-length, L , shown as the red line in Fig. 1 corresponding to the length of the curve that extends from the center of the rule to the end of the radius of the channel. Before the crease is formed, this length of line is equal to the half width of the channel, $c/2+r_c$. During creasing, the length can be determined as the sum of the components wrapped around the rule and channel and the free-span between. The dimensionless crease draw, β , is defined as the increase in length at maximum displacement compared to the initial length, $c/2+r_c$:

$$\text{Crease draw: } \beta = \frac{\Delta L}{r_c+r_b+t} = \theta - \tan(\theta) + (1+\lambda)(\sec(\theta) - 1) \quad (5)$$

which reduces to $\beta=\theta-\kappa$ for $\lambda=0$. With some manipulation, it can be shown that:

$$\frac{\partial \beta}{\partial \kappa} = \frac{\partial L}{\partial z} = \sin(\theta) \quad (6)$$

which is quite a simple result showing that the change in crease draw-length per change in crease displacement is only a function of the crease angle.

As long as the clearance is positive, the crease angle increases following Eq. 3 and remains less than 90° . If the clearance equals zero, the angle follows Eq. 3 up to 90° , at which point $\kappa=1$. For displacements $\kappa>1$, the angle remains at 90° , and the increase in crease draw-length equals the increase in crease depth. If the clearance is negative, the equations given previously are only valid up to a critical displacement. This critical displacement, κ_{cr} , is the point where compression in the thickness direction is required

for a deeper crease. The critical displacement occurs when:

$$\kappa_{cr} = 1 - \sqrt{|\lambda|(2+\lambda)}, \text{ for } \lambda < 0 \quad (7)$$

$$\theta_{cr} = \sin^{-1}(1+\lambda), \quad (8)$$

$$\beta_{cr} = \sin^{-1}(1+\lambda) - (1+\lambda) \quad (9)$$

We found that as the crease depth approaches, the critical displacement, $\frac{\partial \theta}{\partial z}$, increases rapidly, and it would take little increase in draw to wrap around the tooling the full 90° . Although we cannot easily derive an expression for the maximum transverse shear, we can approximate the crease draw as:

$$\beta = \beta_{cr} + \kappa - \kappa_{cr} \quad (10)$$

The dimensionless crease draw can be translated to terms that describe the deformation along the crease. The draw length, D , is the absolute increase in length relative to $c/2+r_c$ at the maximum displacement:

$$D = 2\Delta L = 2\beta(r_c + r_b + t) \quad (11)$$

If this draw was fully accommodated by extension of the original length of material across the channel width, without drawing of additional material into the crease, the crease strain, ε , would be:

$$\varepsilon = \frac{D}{c+2r_c} = \beta \frac{r_c+r_b+t}{c/2+r_c} \quad (12)$$

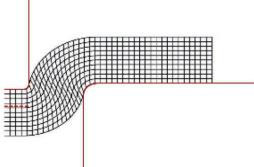
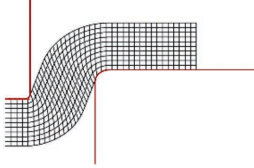
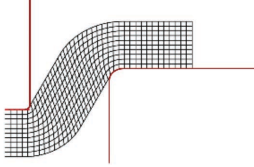
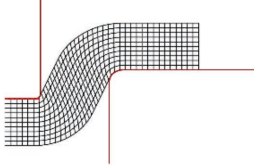
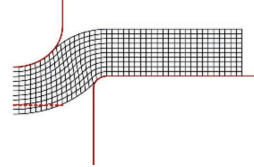
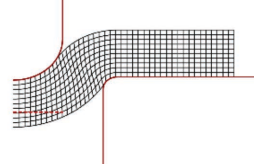
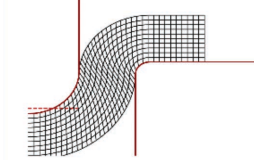
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METHODS AND MATERIALS

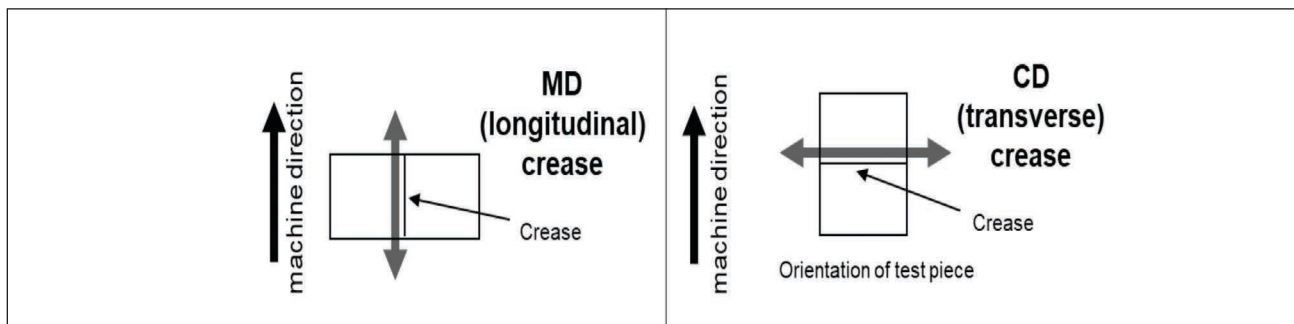
A series of creasing and folding tests were completed on a commercially produced pigment coated solid bleached sulfate (SBS) paperboard (309 g/m², h=0.402 mm) using TAPPI/ANSI Standard Test Methods T 401 “Fiber analysis of paper and paperboard” and T 411 “Thickness (caliper of paper, paperboard, and combined board),” respectively.

The paperboard has coating on one side only. For creasing, the coated side was on the rule/valley side, while the reverse side was on the channel/bead side.

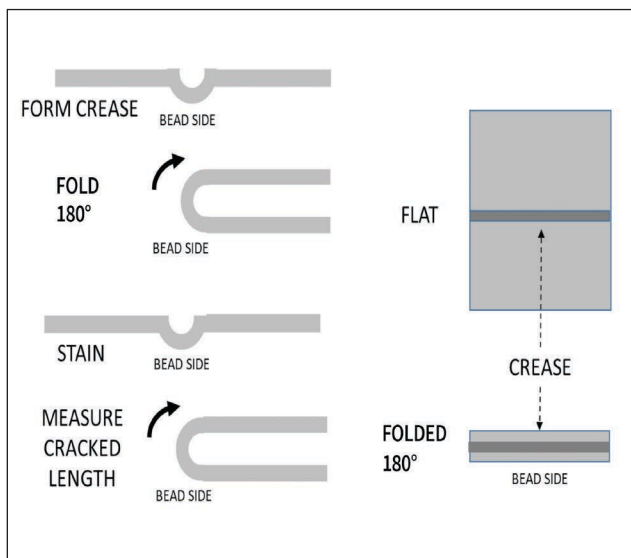
Paperboard samples were creased with a custom laboratory creasing device. The channel segment was mounted to the base structure, and the rule segment was mounted to a linear motor. The linear motor controlled the motion

Set	Rule Type	Crease Shape at Critical ($\lambda < 0$) or Maximum ($\lambda > 0$) Penetration	Tooling Geometry, mm	Nominal Clearance, m	Crease Clearance (λ), mm/mm	Range of Penetration Depths (p), mm
A	flat-tip r: 0.35f		$b = 0.35$ $c = 1.14$ $r_b = 0.04$ $r_c = 0.1$	-0.01	-0.01	-0.05 to 0.20
B	flat-tip r: 0.35f		$b = 0.35$, $c = 1.28$ $r_b = 0.04$, $r_c = 0.1$	0.13	0.12	0.00 to 0.25
C	flat-tip r: 0.35f		$b = 0.35$, $c = 1.48$ $r_b = 0.04$, $r_c = 0.1$	0.33	0.30	0.10 to 0.35
D	flat-tip r: 0.50f		$b = 0.50$, $c = 1.48$ $r_b = 0.04$, $r_c = 0.1$	0.18	0.16	0.00 to 0.25
E	rounded-tip r: 0.70r		$b = 0.70$, $c = 1.14$ $r_b = 0.35$, $r_c = 0.1$	-0.36	-0.21	0.00 to 0.25
F	rounded-tip r: 0.70r		$b = 0.70$, $c = 1.28$ $r_b = 0.35$, $r_c = 0.1$	-0.22	-0.13	0.05 to 0.30
G	rounded-tip r: 0.70r		$b = 0.70$, $c = 1.48$ $r_b = 0.35$, $r_c = 0.1$	-0.02	-0.01	0.15 to 0.40

II. Crease tooling and settings. (For the case where the clearance is negative, the figure shows the crease shape at the critical penetration and the dashed red line shows where the rule would be at the maximum penetration tested.)



2. Orientation of the paperboard for machine direction (MD) creases and for cross direction (CD) creases.



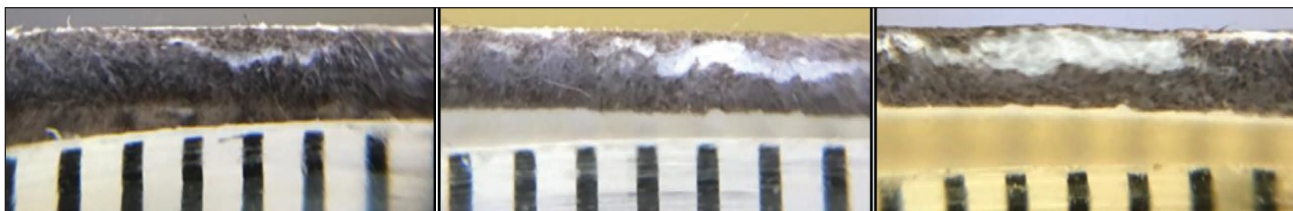
3. Steps for evaluating the cracked length. The diagrams on the left show the paperboard viewed in cross-section. The diagrams on the right show the paperboard viewed from the bead side. The cracked length is determined as a percentage of the length of the crease, as shown on the right side.

of the rule to a target penetration depth, p , (± 0.005 mm) as reported in **Table II**. The velocity of the rule tip was 160 mm/s at point of contact with the paperboard. At this velocity, the total contact time of the rule with the paperboard was ~ 10 ms. The tool segments (14 mm x 20 mm x 85 mm) are made of hardened steel, with a dimension tolerance of (± 0.02 mm). For the tooling used in this study, the rule width, b , and channel width, c , are given in Table I. The rules (A-F) were 50.8 mm long and 1.5 mm high, with either a flat tip profile having a 45° chamfered edge (A-F) or a rounded tip (G and H). The channels were 51.4 mm

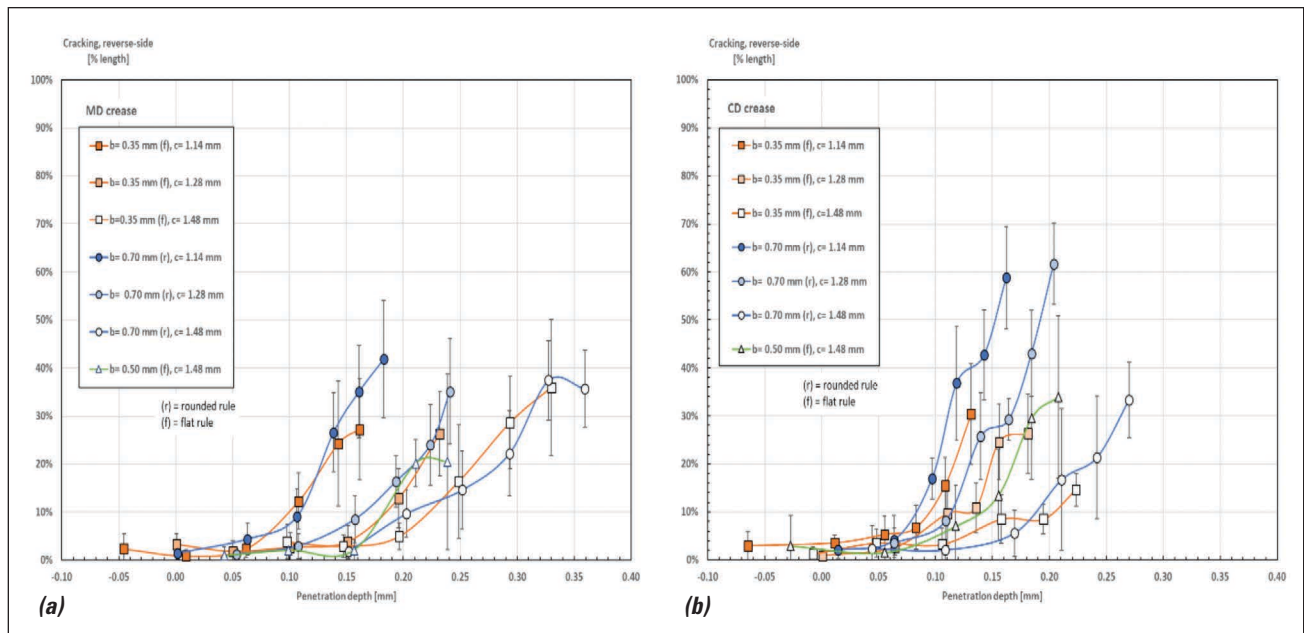
long and 1.0 mm deep with a 45° chamfered edge. Table II also provides a sketch of the crease at maximum penetration for each set of tooling geometry, as well as the dimensionless clearance and crease depth.

Paperboard was preconditioned to 20% relative humidity (RH), and then conditioned at 50% RH for testing. Strips were cut to 102 mm x 305 mm. The strips were clamped on the narrow ends, with one clamp fixed to the base and the other clamp mounted on a slide. The sample was held under a tension using weights attached to the slide clamp. The applied weight was 11.3 kg (25 lb). The rule and channel were oriented so that they were parallel to the short dimension of the sample. In this configuration, the applied tension was perpendicular to the crease. Strips were creased in both the machine direction (MD) and the cross direction (CD) aligned with the creasing tools. Creases where the axis was aligned in the MD of the paperboard were designated as MD creases, and creases aligned in the CD of the paperboard were designated as CD creases (**Fig. 2**). Eighteen creases were produced on each strip and were evenly spaced along the longer length of the strip. The height and width of each crease was measured.

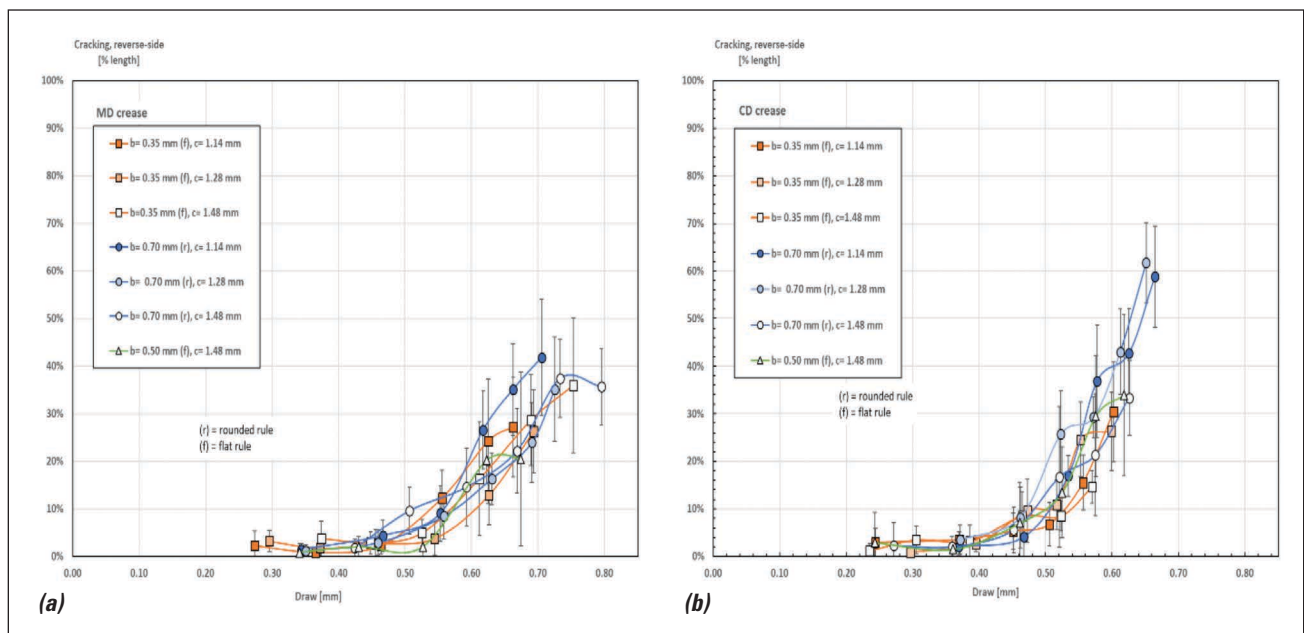
Cracking was evaluated by folding the crease 180° opposite to the bead side, folding back to flat, applying stain to the creased region, and then refolding back to 180° (**Fig. 3**). Note that this is not the conventional direction for folding, but was done this way to detect any cracks that form on the bead side. Stain was used to provide contrast between the surface and the interior and to better highlight the cracks. The length of cracked surface was then measured with the assistance of a 3x magnifier to a precision of 1 mm (see examples of cracks in **Fig. 4**). The degree of cracking is reported as the percentage cracked length per total creased length.



4. Examples of reverse-side cracking, with a mm scale.



5. Reverse-side cracking vs. creasing penetration depth. Error bars are 95% confidence intervals.



6. Reverse-side cracking curves converge when plotted against draw, Eq. 11. Error bars are 95% confidence intervals.

RESULTS

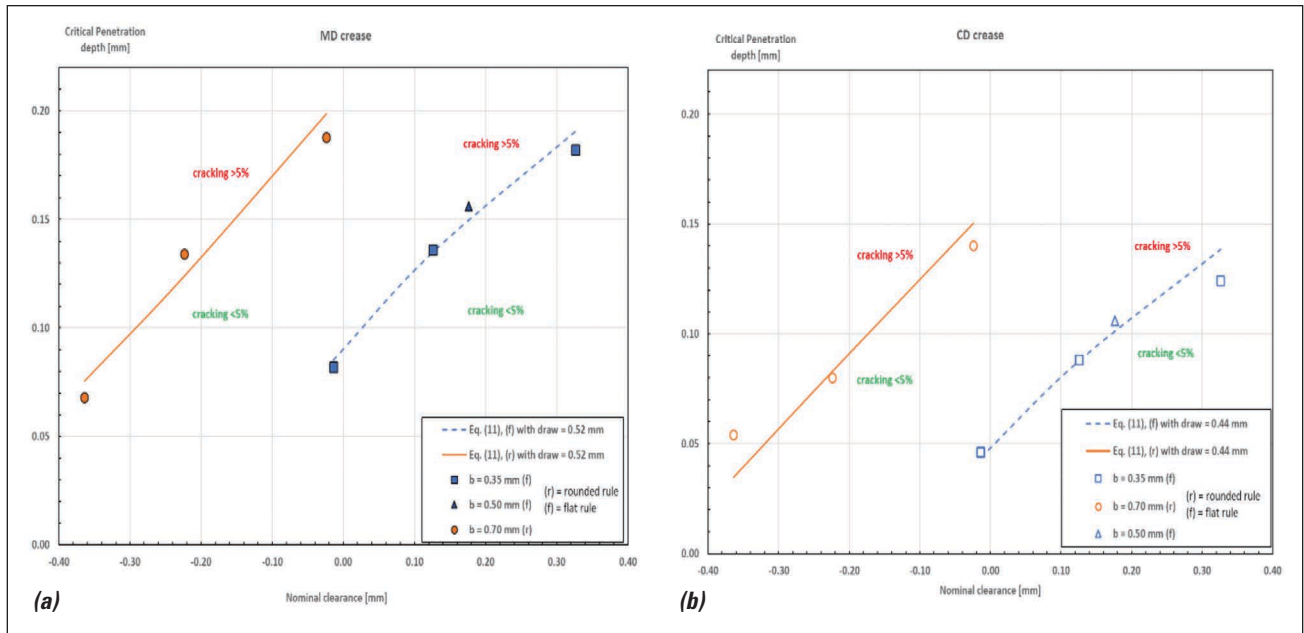
Figure 5 shows the degree of reverse-side cracking versus the penetration depth for the range of tooling. These curves have a characteristic shape: low (<5%) cracking at lower penetration depths, and then an increase in cracking at higher penetration depths. The critical penetration depth is defined as the point where cracking equals 5%.

For the creasing parameters, the draw (D), Eq. 11, produced the best convergence of the curves (**Fig. 6**), particularly to the point at which the cracking transitioned from low cracking. Note that other input parameters, such as

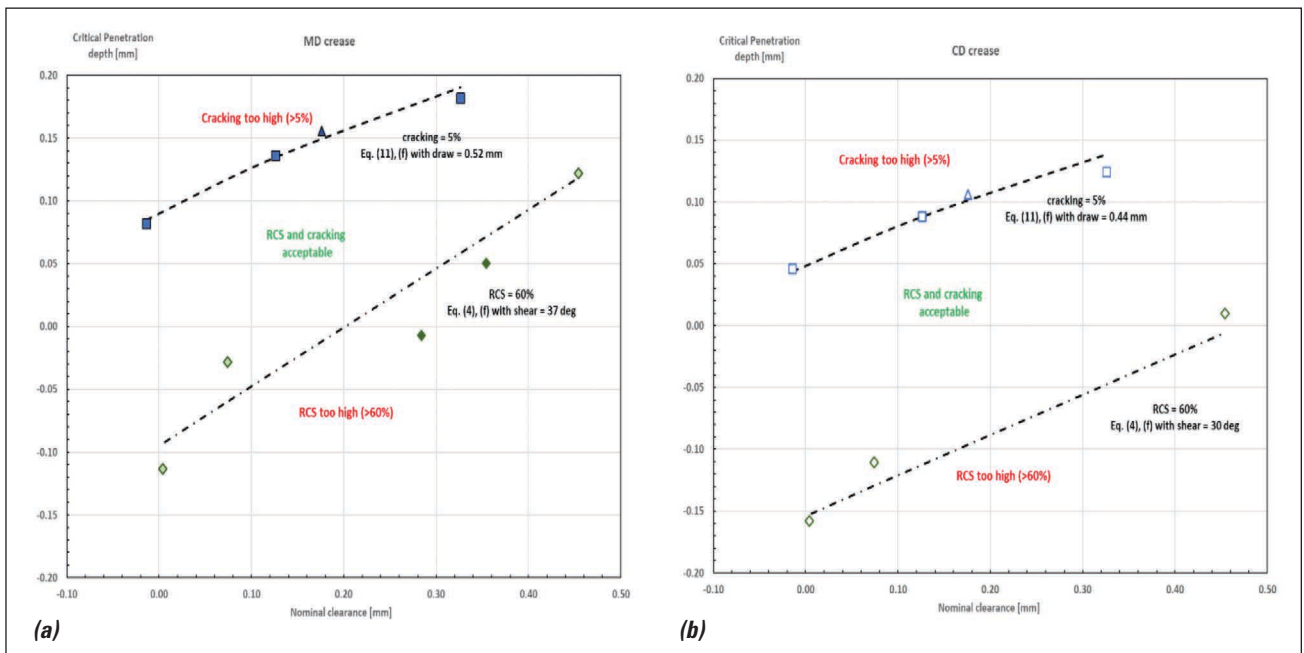
transverse shear strain (Eq. 4) and creasing strain (Eq. 12), did not converge the data as well and are not shown here.

DISCUSSION

The draw length, D , was found to be the best parameter for converging the cracking curves. The draw describes the additional length of paperboard required to form the crease. This increase in length is accommodated by either drawing additional paper into the crease or stretching the paper over some length. In reality, it is some unknown combination of both draw and stretching, but it provides a



7. Critical penetration depth (cracking = 5%) vs. nominal clearance, with lines of constant draw for flat-tip and rounded-tip rules. Penetration depths below these lines will show minimal cracking (<5%).



8. Operating window for flat-tip rules, demonstrating the range of acceptable penetration depths for a given nominal clearance. The diamonds are points from data in [2].

measure of the severity of the creasing operation. It is reasonable that once a critical deformation is exceeded, the surface will crack. It is important to note that the draw is a length, not a strain. We were unable to find a characteristic dimension of the tooling, such as channel width, that yielded a consistent strain. There is likely a gage length that is characteristic of the whole creasing system, which would convert the draw into a strain; however, at this point, we have no means from which to determine this length. Ad-

ditional critical experiments with further extensive changes to the system are required to determine this factor.

The critical draw describes the point at which cracking becomes more severe; in other words, where the cracking transfers from stable and minimal (<5%) to unstable and significant. With a plot of penetration depth vs. clearance, lines of constant critical draw provide a practical means to designate this threshold. Points for critical penetration depth were determined from the data as the depth at which the

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amount of cracking became greater than 5%. The data shows a monotonic increase that follows the critical draw, with separate lines for MD and CD creases, and for rounded-tip and flat-tip rules (**Fig. 7**). It should be noted that the value of critical draw of 0.52 mm for MD creases and 0.44 mm for CD creases was the same for both rounded and square-tip rules.

The full operating window concept can then be demonstrated by including crease strength data on the same paperboard from our previous work [2]. **Figure 8** includes critical penetration depth (RCS = 60%) from the data and lines of constant creasing shear, which relate to an RCS of 60%. This plot gives guidance on the tooling and penetration depth combination that will maintain creasing at an acceptable level. The convertor can then choose a penetration depth that is deep enough to give an acceptable RCS, without going too deep to produce cracking.

CONCLUSIONS

It was shown that 180° reverse side cracking could be characterized by a single parameter, the draw length. The draw length, defined as the increase in length of the board in the channel during creasing, is a function of tooling geometry, board caliper, and rule penetration. The crease draw can be computed for creasing that would cause Z direction (ZD) compression, whereas the previously derived expression for crease shear strain is limited to cases with no ZD compression. Together the crease draw and the crease shear

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angle provide two parameters that one can use to characterize the severity of creasing.

For the paper tested, a critical draw of 0.52 mm for MD and 0.44 mm for CD corresponded to 5% cracking along the length of the crease. Keeping the draw below this level should lead to creased samples with minimal cracking. By taking this data, along with previous data for reduction in relative crease strength, an operating window for creasing parameters can be formed, as shown in Fig. 8. Plotting penetration depth vs. nominal clearance gives a practical means to describe the threshold from minimal (<5%) to severe cracking and reduction in relative crease strength. A line of constant draw forms the upper bound and a line of constant shear forms the lower bound.

ABOUT THE AUTHORS

We chose to study this topic because we wanted to provide a stronger theoretical framework for describing creasing severity, which will enable calculation of the optimal tooling for an application. There have been very few articles that address the effect of creasing conditions on crease cracking.

In our previous work, we focused on quantifying the transverse shear strain that occurred during creasing and demonstrated how the relative crease strength (RCS) upon folding correlated with this value. In this work, it was shown that 180° reverse side cracking could be characterized by a single parameter, the draw length. It was especially interesting how well that one parameter (draw length) could converge the cracking curves. The most difficult aspect of this study was the time and effort required to translate a finding in the laboratory to a conference presentation and then to a journal article.

For mills, the creasing operating window plot gives guidance on the tooling and penetration depth combination that will maintain creasing at an acceptable level. Paperboard convertors can then choose a penetration depth that is deep enough to give an acceptable relative crease strength (RCS), without



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going too deep to produce cracking. Mills can also benefit by determining the factors that create a wider operating window.

Our next step is to identify a non-dimensional parameter to describe the cracking threshold. The draw length is an absolute length, so is not clearly transferable to other systems.

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