THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

# BEHAVIOR OF FIBROUS AND NONFIBROUS COMPONENTS IN THE CORRUGATING OPERATION

## PART V. STATE OF STRESS AT PRESSURE ROLL NIP

Project 1108-22

Report Eight

A Progress Report

to

TECHNICAL COMMITTEE
FOURDRINIER KRAFT BOARD INSTITUTE, INC.

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## SUMMARY


A study was made, employing high-speed photographic technique, of the behavior of the corrugated medium approaching the pressure roll nip, in the pressure nip and discharging from the pressure nip under a variety of conditions using one sample of 26-lb. semichemical medium. The conditions varied were the direction or angle of take-off and the relative speed of pressure roll to corrugating roll.

The results of the study indicate that, based on the one sample used, there is visual evidence that the fluted medium drops off the end of the finger and is momentarily suspended in mid-air. It was observed that the distance which the flute drops follow in many instances a regular pattern with frequent reversals. That is to say, successive flutes tend to drop in an alternate pattern of large and small amounts. In some cases it has been possible to associate an excessive drop off with a large difference in flute height of the two flutes involved.

Based on average caliper, average difference in height of consecutive flutes and maximum difference, best results were obtained when the take-off was 15° below normal.

# INTRODUCTION

Corrugated board has been in existence for a comparatively long time and although much is known about machinery design and operation, relatively little is known about the fundamentals of corrugating in terms of the stresses and strains to which the medium is subjected and the behavior of the medium in such a stress-strain environment. That this is a significant area, one need only reflect that essentially the array of machinery and its mode of operation are designed for one purpose, namely, to stress the medium under environmental conditions and to such a degree that it molds, i.e., undergoes a permanent set and thereby retains a fluted shape to which the liners are adhered. Thus, the heart of the corrugating operation is basically a matter of the state of stress and strain induced in the medium while in a suitable environment for molding. It may be expected that the limiting factor of corrugating (runnability or high-low corrugations) is directly related to the type and magnitude of the stresses and strains imposed on the medium during the corrugating and the behavior of the medium when exposed to these stresses and strains.

Sometime ago an exploratory theoretical and experimental investigation of corrugating based on the concept of the stress-strain behavior of the medium was carried out (1). This study was concerned with an analysis of the state of stress and strain induced in the medium (in contrast to the allowables of the medium) by the corrugating operation up to the center of the corrugating labyrinth. The results of this study indicated that from a mechanics of material standpoint, corrugating may be viewed as a process wherein an array of machinery imposes sufficiently large stresses and strains on the medium while forming and subsequently molding it to the shape of a flute under conditions of elevated temperature, so that the medium suffers a permanent set and thereby retains the fluted shape upon leaving the labyrinth of the corrugating rolls. The molding process may, for convenience, be treated as a two-step process involving (a) formation of the fluted contour, followed by (b) setting the flute when it undergoes severe transverse compression at the nip of the corrugating rolls.

The medium fractures if the induced stresses exceed the strength of the medium under the prevailing conditions of heat, moisture, and rate of stressing. It is believed that, in general, rupture, if it occurs, does so during the first step in molding, that is, about one or two "teeth" ahead of the center of the labyrinth. At this point the medium which is under transport, bending, shear, and transverse compression strains, has attained nearly the full flute shape but has not been subjected to the large transverse compression which takes place at the center of the labyrinth and which "completes" the holding — induces permanent set at flute tips.

The state of stress and strain in the medium during formation of a flute may be considered as the sum of two parts: (a) the tensile stress and strain acquired during transport of the medium from the parent roll to the point where the flute is formed (this stress is sensibly uniform across the thickness of the medium), and (b) the stresses and strains of forming (bending, shear, and transverse compression) resulting from severe local deformation of the medium as it attains the fluted shape (bending and shear stresses vary in intensity across the thickness of the medium).

Subsequent to the above study, investigations were carried out relative to the behavior of the medium and the effect of finger design and clearance on the formation of high-low corrugations (2); and a comparison of the profile of consecutive flutes formed on the commercial boards (3). The results of these two studies indicated that the finger design and clearance had little influence on high-low flutes until excessive deviations from normal were used. In addition, it was found that corrugated board made on various commercial corrugators exhibited a basic high-low flute profile on single-faced boards which were acceptable and represented normal commercial quality fabrication. These results indicate that the mechanism of corrugating induces a basic high-low flute configuration which, under normal conditions, does not interfere with subsequent conversion or quality.

The present report is concerned with an analysis of the state of stress and strain induced in the medium in the area of the pressure roll nip. It has been established that flute fractures, if they occur, are induced prior to the center of the corrugating labyrinth. On the other hand, based on the results obtained by means of high-speed photography in Reference (1) there is no visual evidence that high-low flutes are present in the corrugating labyrinth or formed by "pulling out" flutes which have already been formed. There is some evidence that on emerging from the corrugating labyrinth all flutes do not bottom the same amount. In addition, the photographic evidence obtained in connection with the high-speed photography of the behavior of the medium during the corrugating operation (4) shows that after the fluff-out point the fingers force the fluted medium into better mesh with the bottom corrugating roll than existed prior to the fluff-out point. There is little evidence of high-low corrugations existing after the fluff-out and prior to the pressure nip. The foregoing is, of course, based on visual examination by side or edge viewing of the medium. There is a question as to whether the edge necessarily represents the behavior removed from the edge and also whether the eye is capable of detecting the small differences actually encountered in high-low corrugations.

Because of the foregoing and the rotation which the flutes undergo at the pressure nip, the present study was undertaken to investigate the state of stress and strain to which the medium is subjected during its passage through the pressure roll nip as it may affect high-low corrugations. At least two major activities take place at the pressure nip, i.e., (a) formation of the union between the flute tip and the single-face liner, and (b) the transition of the flutes from a state of rotary motion to linear motion. When the flutes are in mesh with the bottom corrugating roll, the distance between consecutive flute tips is greater than the corresponding difference between the roots or valleys of the flutes by an amount proportional to the difference in their radii. When the board emerges from the pressure roll nip in the form of single-faced board, the distances between flute tips and flute roots are equal. The formation of single-faced board by normal corrugating operation is essentially the generation of rack by a gear. In order to compensate for the dimensional change it is necessary for the flutes to rotate so as to equalize the initial disparity in the distances between flute tips and roots. It was felt that possibly the rotation coupled with the direction of take-off or discharge, i.e., tangentially (at right angle to the line of centers of the two rolls), or a few degrees up or down from tangential, may have a marked effect on the formation of high-low corrugations.

For the purpose of this study a 26-lb. semichemical medium of good runnability was selected. The selected medium was corrugated on the Institute's specially designed experimental corrugator (5) under a variety of conditions in so far as direction of take-off and relative speed of the pressure roll are concerned, using a 42-lb. liner as the facing and starch as the adhesive. The behavior of the medium was observed at various locations in the pressure roll nip by means of high-speed photography. For each condition of take-off and relative pressure roll speed, a high-speed film was taken at three locations showing the behavior at (a) entrance to pressure roll nip, (b) in the pressure roll nip, and (c) leaving the pressure roll nip. The corrugator speed was maintained at 300 f.p.m. and the high-speed films were taken with a Fairchild high-speed 16 mm. motion analysis camera operating at 6000 frames per second.

For each of the locations or positions studied by means of the photographic record, a section of corresponding single-faced board was evaluated for caliper characteristics. To insure a positive relationship between the film and the board sample evaluated, the medium was flagged prior to entering the corrugating labyrinth so that when the flag and medium were simultaneously corrugated, the flag would be visible at a point in the film. The flag consisted of a 0.0003-inch aluminum rectangle (0.5 by 1.0 inch) and applied with splicing tape when the corrugator was at operating speed, i.e., 300 f.p.m.

The conditions studied and the locations or positions photographed are shown in Table I. As previously mentioned, single-faced combined board samples were flagged and average caliper and individual flute height were measured for 80 flutes on each side of the flag. From the individual flute height the average and the maximum difference in the height of consecutive flutes were calculated and represent the tendency to form high-low corrugations.

TABLE I

CONDITIONS AND LOCATIONS PHOTOGRAPHED

| Film No. | Position Photographed | Corrugator Condition: Single-Face Take-Off[a] | Corrugator Condition: Rel. Speed of Pressure Roll to Bottom Corrugating Roll |
|---|---|---|---|
| 190 | entering pressure roll nip | tangential | 0 |
| 191 | center of pressure roll nip | tangential | 0 |
| 192 | discharge from pressure roll nip | tangential | 0 |
| 193 | discharge from pressure roll nip | 15° above tangent | 0 |
| 194 | discharge from pressure roll nip | 15° below tangent | 0 |
| 195 | discharge from pressure roll nip | 15° below tangent | 2% faster |
| 196 | discharge from pressure roll nip | 15° above tangent | 2% faster |
| 197 | discharge from pressure roll nip | tangential | 2% faster |
| 198 | center of pressure roll nip | tangential | 2% faster |
| 199 | entering pressure roll nip | tangential | 2% faster |
| 200 | entering pressure roll nip | tangential | 2% slower |
| 201 | center of pressure roll nip | tangential | 2% slower |
| 202 | discharge from pressure roll nip | tangential | 2% slower |
| 203 | discharge from pressure roll nip | 15° above tangent | 2% slower |
| 204 | discharge from pressure roll nip | 15° below tangent | 2% slower |

[a]Tangential refers to normal condition.

## DISCUSSION OF RESULTS

As previously mentioned, this study was undertaken for the purpose of investigating the effect which the stress-strain conditions prevailing or induced at the pressure roll nip of the single-facer and the direction of discharge from the pressure nip may have on the formation of high-low corrugations. To this end a 26-lb. semichemical corrugating medium was corrugated at 300 f.p.m. under varying conditions of take-off and the behavior of the medium examined by means of high-speed photography. The behavior of the medium was photographed at three different locations:

1. entering the pressure nip;
2. center of pressure roll nip; and
3. discharge from pressure roll nip.

In addition, measurements of average caliper, average difference, and maximum difference in the height of consecutive flutes were measured in the portion of the single-faced board which was photographed.

### 1. BEHAVIOR OF THE MEDIUM

#### A. Entering Pressure Roll Nip

As may be noted in Fig. 1 which is a negative print of two frames of Film 190 (pressure roll and bottom corrugating roll running at same peripheral speed and with tangential take-off), the fluted medium drops off the end of the finger and is momentarily suspended in mid-air. Immediately after drop-off the medium starts to move upward toward the bottom corrugating roll as it travels toward the pressure nip. The start of the upward movement coincides with the contact of the preceding medium flute with the single-faced liner. The upward movement

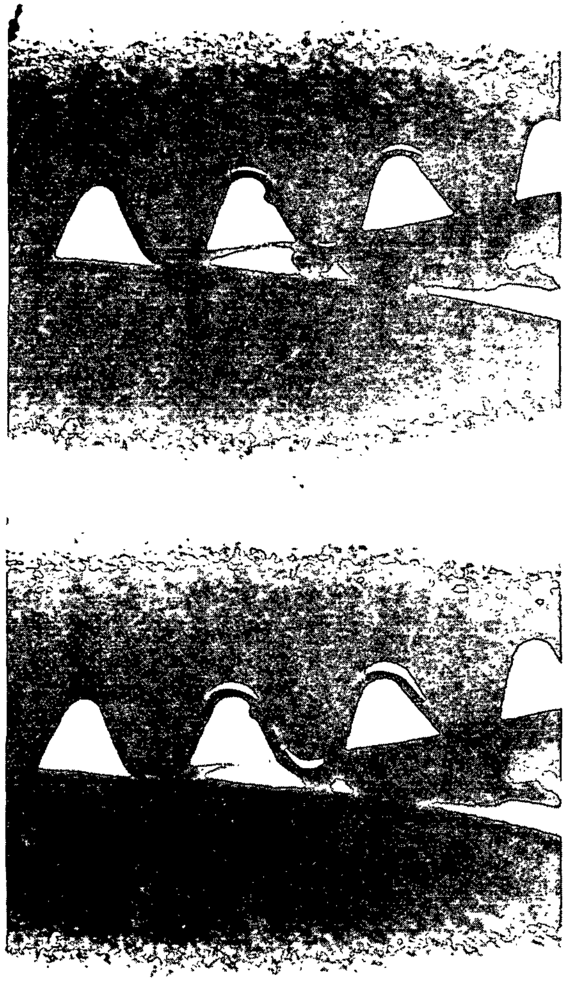

Figure 1. Behavior of Corrugated Board Entering Pressure Roll Nip (Tangential Take-Off; Pressure Roll Same Speed as Bottom Corrugating Roll)

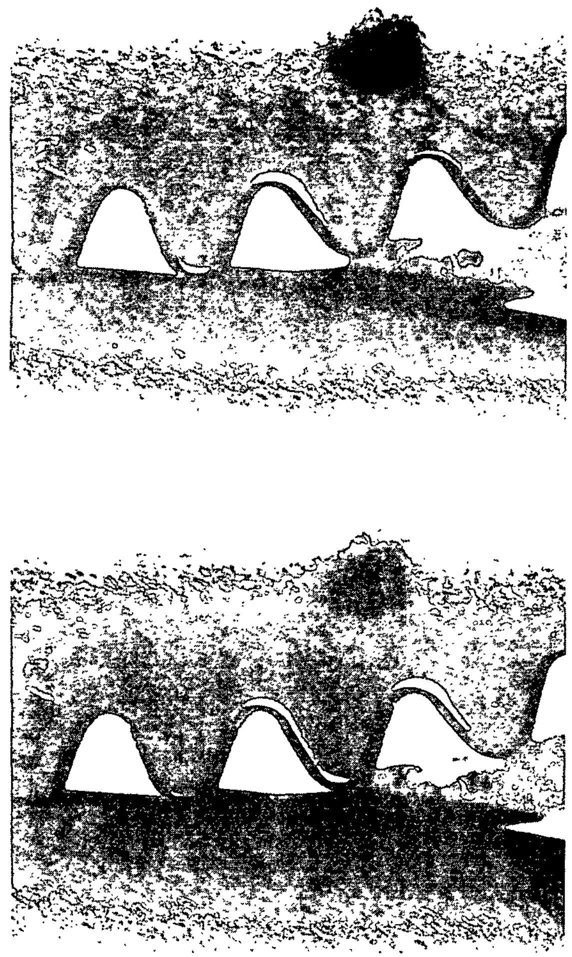

Figure 2

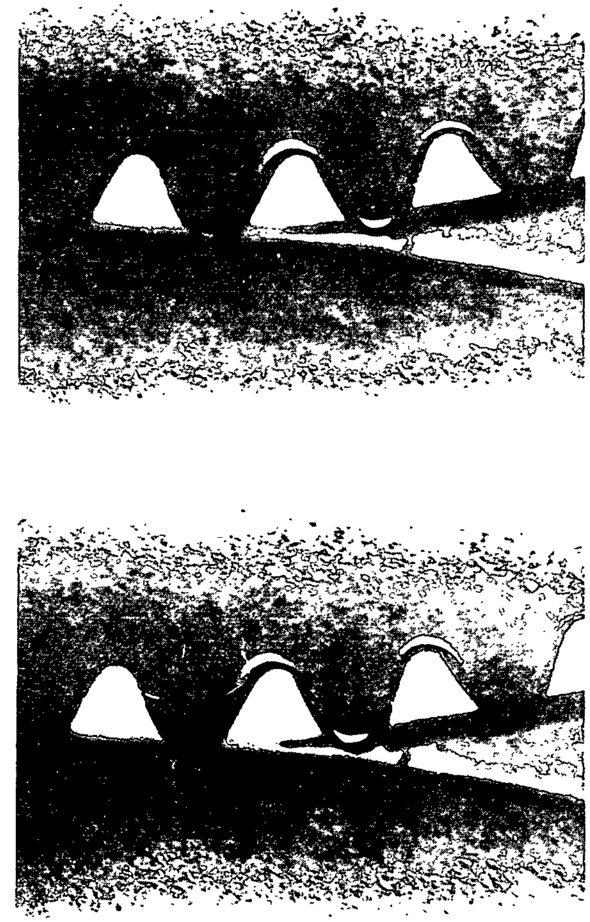

Figure 3

Behavior of Corrugated Medium Entering Pressure Roll Nip (Tangential Take-Off)

Figure 2: Pressure Roll 2% Slower than Bottom Corrugating Roll

Figure 3: Pressure Roll 2% Faster than Bottom Corrugating Roll

of the medium flute continues as the medium flute approaches the nip and the flute progressively becomes again intimately meshed in the bottom corrugating roll. Because of the initial drop, however, the medium flute always contacts the single-face liner prior to the reseating of the medium flute tip and the roll flute tip. As the remeshing of medium and bottom corrugating roll takes place there is a tendency for the roll flute tip on the bottom corrugating roll to bear against the trailing sidewall of the medium as it approaches the center of the pressure nip. This in turn results in the roll flute tip meshing with the fluted medium at a point slightly ahead of its original point of coincidence. This change in tip position manifests itself in two ways: (a) The trailing sidewall or shank of the preceding flute is bulged inward away from the roll flute tip and appears to draw down the sidewall and force the formed flute tip to be slightly forward of its original location relative to the medium itself. This gives a tendency to change the angle of the sidewall on the trailing side of the flute. (b) The excess medium in any flute on remeshing appears to be forced backward relative to the direction of travel and thus would tend to compensate for discrepancies in flute height.

Study of the films revealed that the distance which the medium flute drop follows, in many instances, is a regular pattern with frequent reversals. That is to say, successive flutes tend to drop in an alternate pattern of large and small amounts with frequent reversals in order. In some cases it has been possible to associate an excessive drop-off with a large discrepancy in the flute height of the two flutes involved. It should be borne in mind that the flute which is viewed as dropping off the finger actually constitutes the leading and trailing edges of two consecutive flutes when viewed as single-faced board. In those cases where there is a large drop-off it may be that on remeshing more medium is pushed into the succeeding flute than was engulfed in the first or leading flute.

It would appear from the behavior of the medium used in this study that it would be advantageous from a uniform flute consideration to have the fingers flush against the single-face liner.

High-speed photographs were also taken with the pressure roll geared to operate 2% slower and 2% faster than the corrugating roll (see Fig. 2 and 3). With the 2% faster pressure roll there appeared to be less "crowding" of the medium during remeshing and the drop-off appeared to be more uniform. The 2% slower pressure roll appeared to accentuate the crowding action. This caused the trailing sidewall of a flute to bow inward. The greater drop-off at the finger appeared to give greater disparity in the height of the two flutes involved.

B. Center of Pressure Nip

The behavior of the medium in the center of the pressure nip may be seen in Fig. 4 and 5, respectively, for pressure roll speeds equal to and 2% slower than the bottom corrugating roll. It may be noted that in the center of the pressure nip there are approximately three flutes in contact at any one time in the case of A-flute board. As previously mentioned it may be noted that the medium tip contacts the single-face liner before the roll flute is properly meshed with the medium flute. This possibly could give rise to a shift in the glue line.

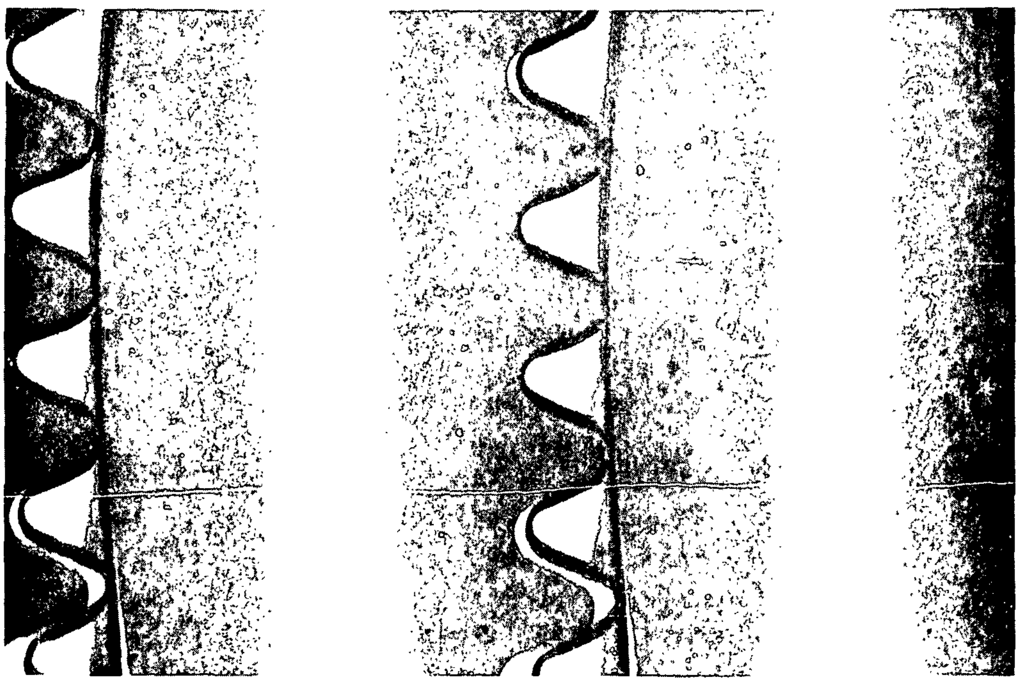

Figure 4

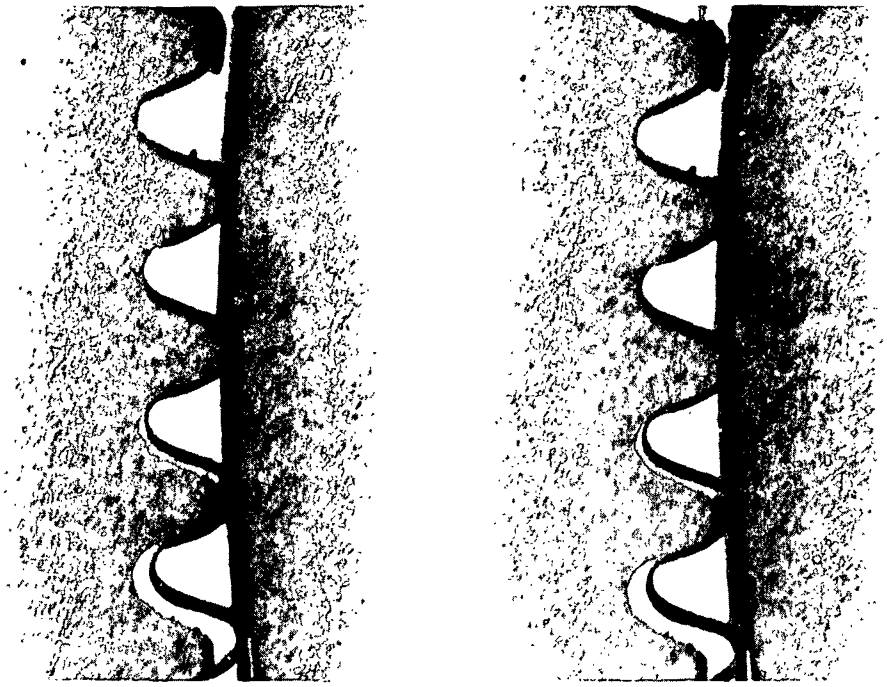

Figure 5

Behavior of Corrugated Medium at Center of Pressure Roll Nip (Tangential Take-Off)

Figure 4: Pressure Roll Same Speed as Bottom Corrugating Roll
Figure 5: Pressure Roll 2% Slower than Bottom Corrugating Roll

When the pressure roll was operated 2% slower than the bottom corrugating roll there was a tendency for the fluted medium tip to slide forward on the liner as it approached the center of the pressure roll. This sliding action has the effect of compacting or compressing the width of the flute on the liner, yielding flutes of steeper sidewall and higher flute caliper. The higher caliper flutes being forced to stay within the confines of the fluted roll resulted in a pronounced flexing of the trailing sidewalls while they passed through the center of the pressure nip.

C. Discharge from Pressure Roll

As previously mentioned the form of the single-faced board through a union of the corrugated medium and single-face liner is similar in many respects to the rack generated by a gear. In the case of corrugated board it would seem desirable that the board be subjected to as little stress as possible after the pressure nip because the "green" or initial bond formed in the pressure nip is believed to be quite weak. The single-faced board is fully meshed with the bottom corrugating roll at the center of the pressure nip. As the board emerges it moves along a line normally parallel to the line of generation — tangentially. The flute tips on the bottom corrugating roll have a horizontal and a vertical velocity component. It would seem that if the vertical movement is not fast enough for the lateral movement of the single-faced board, stresses may be imposed on the single-faced board which would impair its quality. For this reason high-speed photographs were taken at the discharge side of the pressure nip when the single-faced board was discharged normally (tangentially), 15°

above and 15° below the normal when the speed of the pressure roll was equal, 2% faster and 2% slower than the speed of the bottom corrugating roll.

Typical negative prints of frames taken from high-speed films taken of the discharge side of the pressure roll for tangential, 15° above and 15° below the normal with the pressure roll speed equal to the bottom corrugating roll are shown in Fig. 6, 7, and 8, respectively. As may be seen in Fig. 6, when the single-faced board is discharged tangentially, the roll flute moves upward and outward as the single-faced board moves outward. It appears that possibly the roll flute tip may drag or press slightly against the trailing sidewall of the medium flute. This condition could give rise to flute distortion such as leaning flutes or possibly even high-low corrugations. All flutes appeared well "bottomed" in the bottom corrugating roll on emerging from the center of the pressure nip. An illustration of the interference mentioned above may be seen in Fig. 7 which shows the condition when the single-faced board is discharged 15° above the normal or tangential. Under these conditions the single-faced board remains in contact with the bottom corrugating roll for a much longer distance on the discharge side. Further, because of the change in geometry (in contrast to tangential discharge), the single-faced board now has a vertical velocity component and the roll flute tip rides against the trailing sidewall of the medium flute. This causes a pronounced inward bowing of the sidewall resulting in distorted flutes. Occasionally, displacement of a flute was evident in the film. The other extreme, namely, discharging 15° below the normal, may be seen in

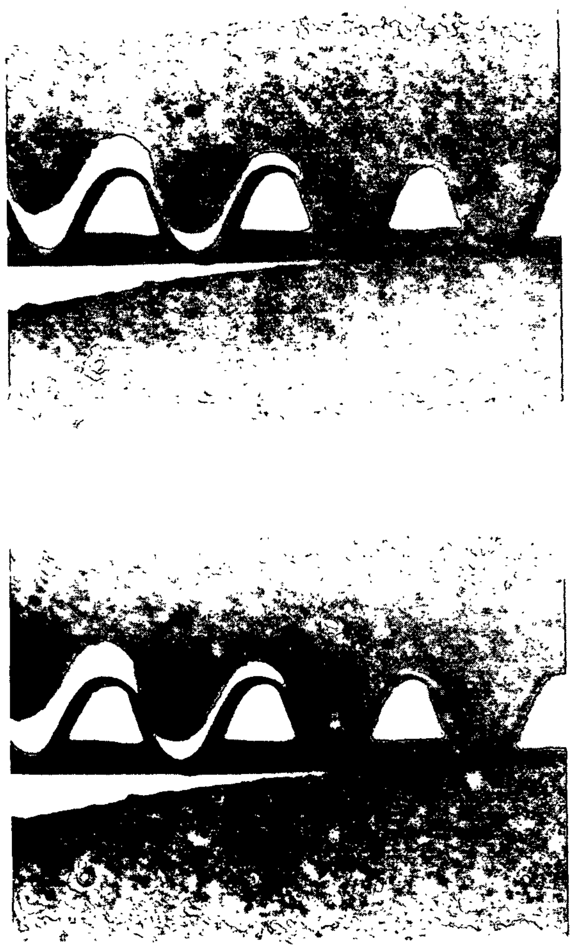

Figure 6

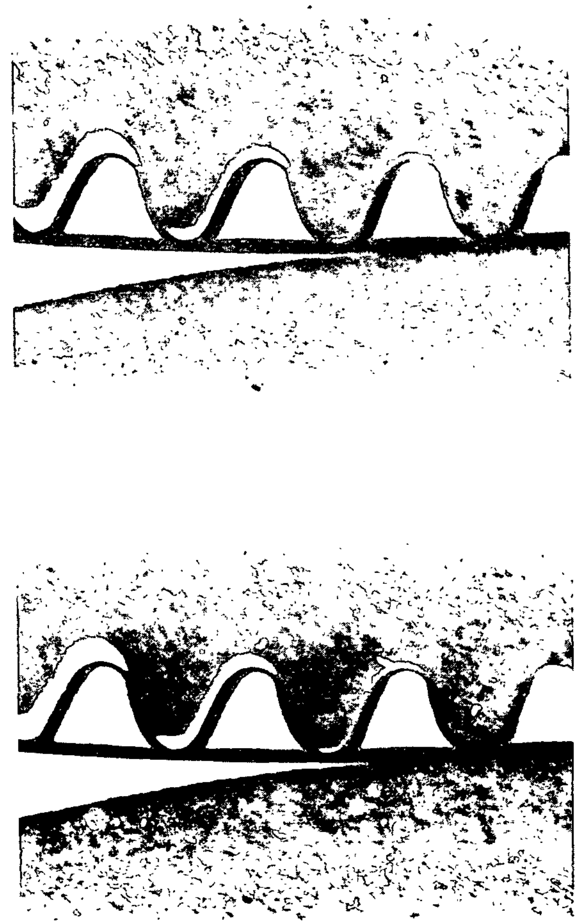

Figure 7

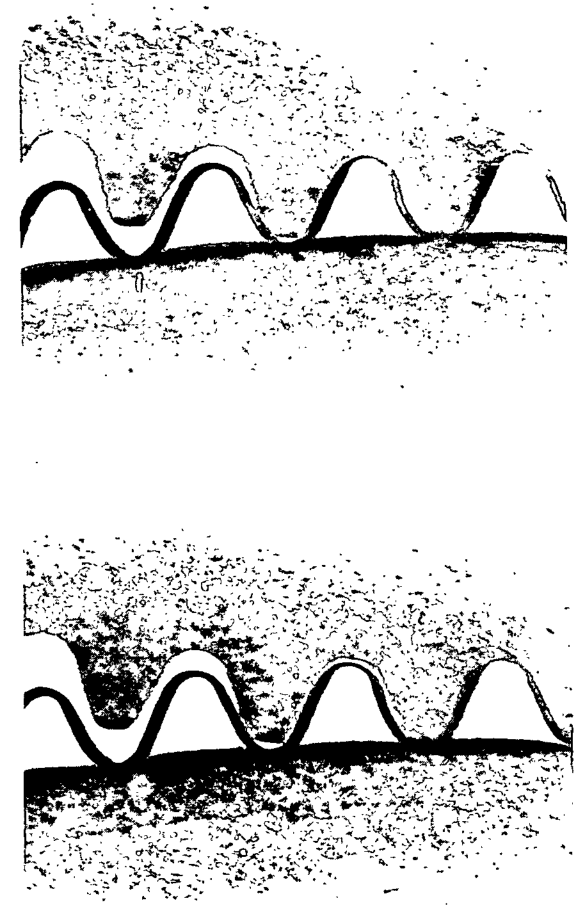

Figure 8

Behavior of Corrugated Board Discharging from Pressure Roll Nip (Pressure Roll Speed Equal to Bottom Corrugating Roll Speed)

Figure 6: Tangential Take-Off
Figure 7: Take-Off 15° Above Normal
Figure 8: Take-Off 15° Downward from Normal

Fig. 8. It may be observed that the tip of the roll flute clears the medium flute with no evidence of dragging. Also, the flutes emerging from the center of the pressure roll appear to be well bottomed. Comparison of the behavior of the single-faced board in the three conditions above indicate that a discharge slightly below normal may be advantageous.

The corresponding behaviors when the pressure roll was operated 2% under and over are shown in Fig. 9-11 and Fig. 12-14, respectively. When the pressure roll was operated 2% slower than the bottom corrugating roll the "drag" on the medium flute appears to be much greater than when operating at the same speed. Occasionally, displacement of flutes was observed. When the pressure roll was operated at 2% faster speed, the sidewall drag appeared about the same as when operated at the same speed as the bottom corrugating roll. It was observed, however, that the flute spacing (distance between flutes) is noticeably greater.

2. EFFECT ON FLUTE CALIPER

For each of the conditions studied by means of photographic technique, a section of corresponding single-faced board was sampled and evaluated for flute height characteristics. As previously mentioned, to insure a positive relationship between film and the board sample used, the medium was flagged on the corrugator so that both the flag and the medium were visible in the film. Caliper measurements, i.e., average caliper, average difference in the height of consecutive flutes and maximum difference in consecutive flutes, were made on 80 flutes adjacent to the flag on each side. The results reported in Table II represent the average of the 160 consecutive flutes.

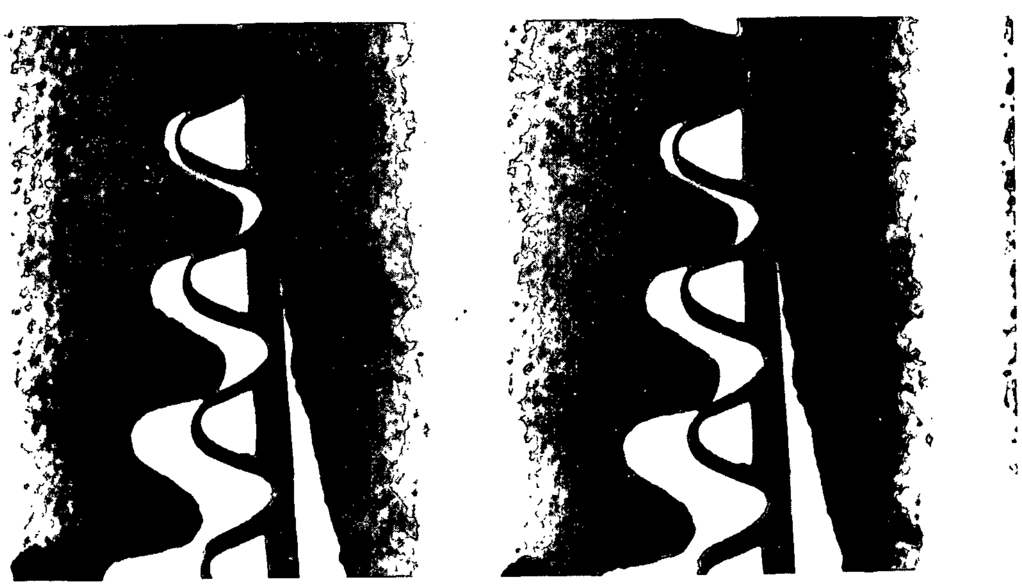

Figure 9

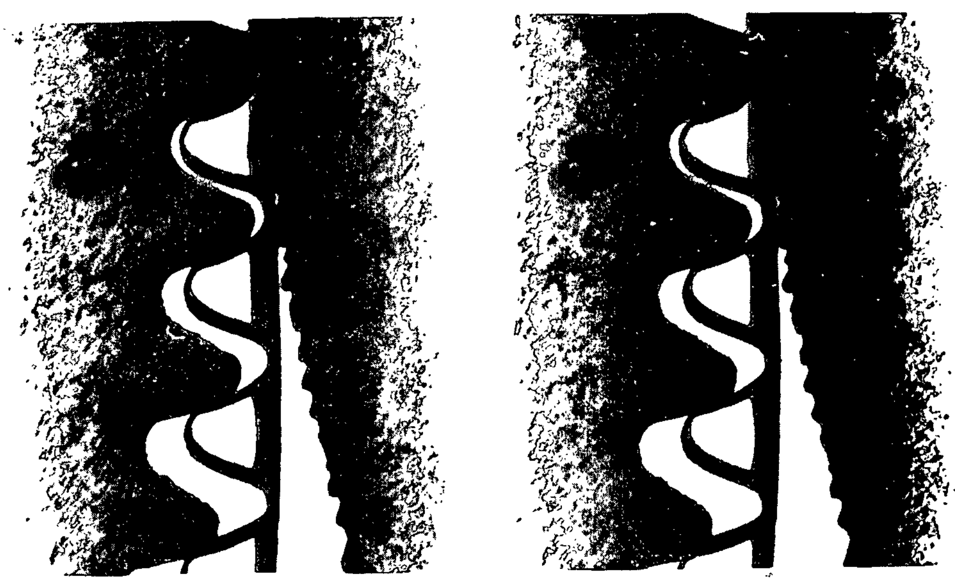

Figure 10

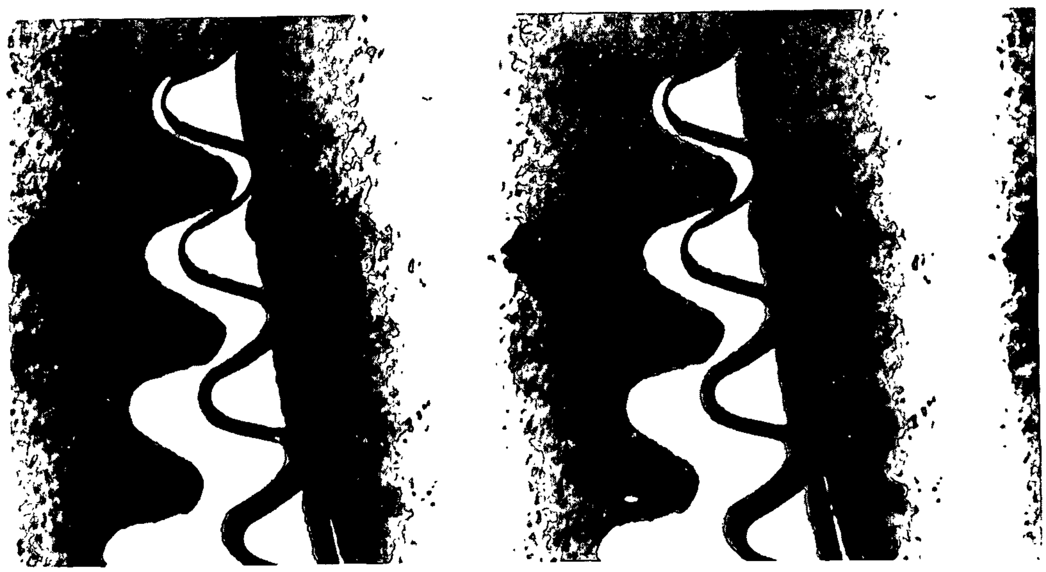

Figure 11

Behavior of Corrugated Board Discharging from Pressure Roll Nip (Pressure Roll 2% Slower Speed)

Figure 9: Tangential Take-Off
Figure 10: Take-Off 15° Upward from Normal
Figure 11: Take-Off 15° Downward from Normal

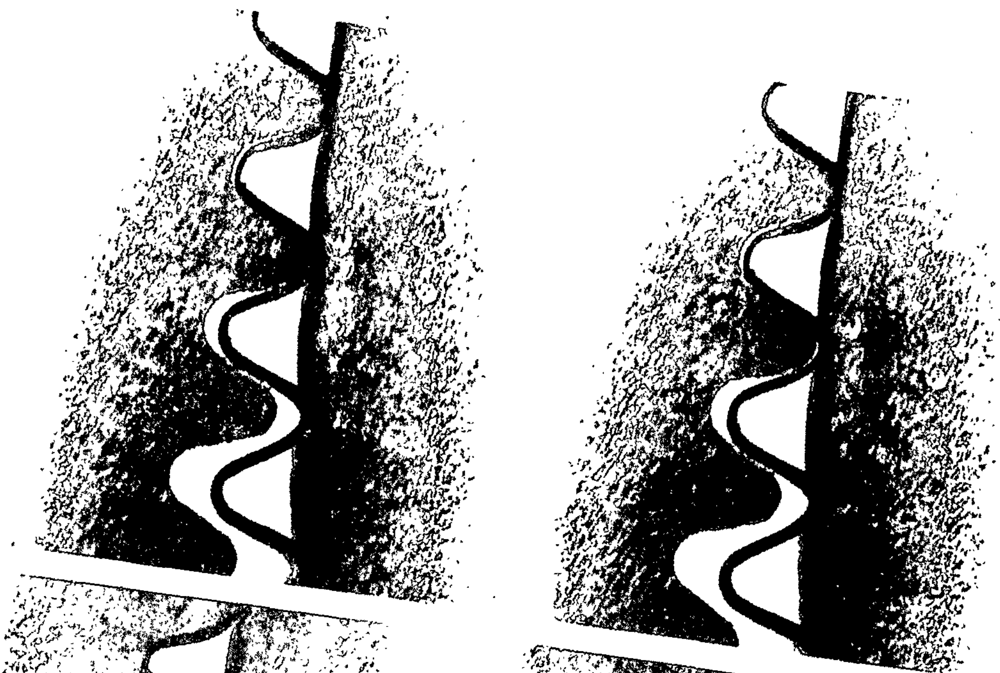

Figure 14

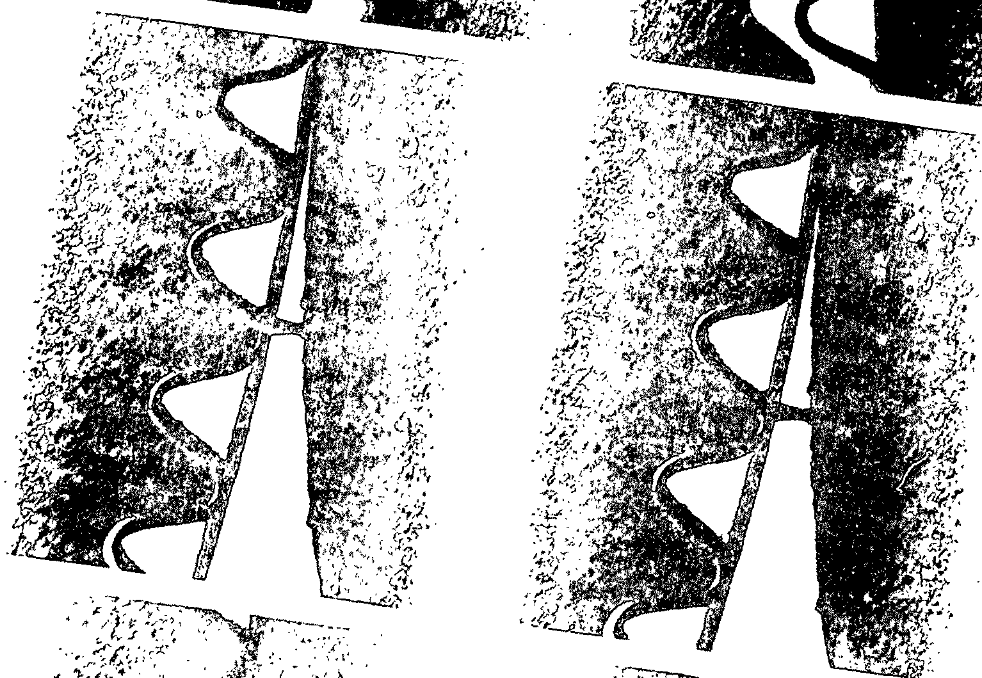

Figure 13

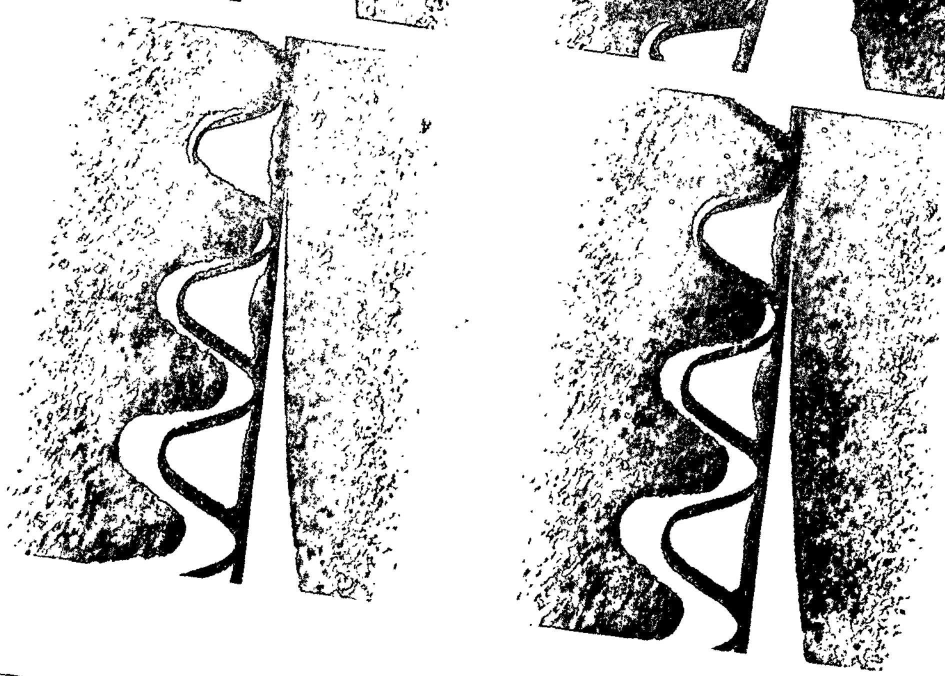

Figure 12

Behavior of Corrugated Board Discharging from Pressure Roll Nip (Pressure Roll 2% Faster Speed)

Figure 12: Take-Off Normal
Figure 13: Take-Off 15° Upward from Normal
Figure 14: Take-Off 15° Downward from Normal

TABLE II

FLUTE HEIGHT CHARACTERISTICS

| Film No. | Relative Speed Pressure: Corr. Roll | Single-Faced Board Discharge | Flute Characteristics, pt. Average Caliper | Average Difference[a] | Maximum Difference[a] |
|---|---|---|---|---|---|
| | | **Effect of Take-Off** | | | |
| 192 | 0 | Tangential or normal | 205.2 | 1.1 | 5.8 |
| 193 | 0 | 15° above normal | 204.7 | 1.8 | 17.2 |
| 194 | 0 | 15° below normal | 204.7 | 0.8 | 3.1 |
| 197 | 2% faster | Tangential or nornal | 201.8 | 1.9 | 7.1 |
| 196 | 2% faster | 15° above normal | 201.0 | 2.6 | 15.5 |
| 195 | 2% faster | 15° below normal | 205.0 | 1.5 | 5.8 |
| 202 | 2% slower | Tangential or normal | 205.6 | 1.4 | 18.3 |
| 203 | 2% slower | 15° above normal | 207.8 | 3.4 | 31.0 |
| 204 | 2% slower | 15° below normal | 206.6 | 1.3 | 5.4 |
| | | **Effect of Relative Speed of Pressure Roll** | | | |
| 192 | 0 | Tangential or normal | 205.2 | 1.1 | 5.8 |
| 197 | 2% faster | Tangential or normal | 201.8 | 1.9 | 7.1 |
| 202 | 2% slower | Tangential or normal | 205.6 | 1.4 | 18.3 |
| 193 | 0 | 15° above normal | 204.7 | 1.8 | 17.2 |
| 196 | 2% faster | 15° above normal | 201.0 | 2.6 | 15.5 |
| 203 | 2% slower | 15° above normal | 207.8 | 3.4 | 31.0 |
| 194 | 0 | 15° below normal | 204.7 | 0.8 | 3.1 |
| 195 | 2% faster | 15° below normal | 205.0 | 1.5 | 5.8 |
| 204 | 2% slower | 15° below normal | 206.6 | 1.3 | 5.4 |

[a] Difference in height of consecutive flutes.

Based on the results obtained on the sample of board used in this study, the take-off 15° below normal (tangential) gave the best results in so far as the lowest average and maximum difference in the height of consecutive flutes were concerned. There appeared to be no clearly defined difference in over-all board caliper. The worst condition was with a 15° above normal take-off.

The effect of pressure roll speed appeared to vary with the type of discharge. When the take-off was 15° below normal the effect of pressure roll speed was minimum.

The above results were obtained on one sample of medium, and, therefore, should be interpreted with this limitation.

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