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ABSTRACT

The investigation is concerned with strategies to reduce losses in medium compressive strength during corrugating.

Medium handsheets with a non-random fiber orientation were made using a NSSC pulp and different levels of synthetic fiber addition, including glass and kevlar pulp, at two levels of wet pressing. Corrugating was performed using a concora fluter, and compressive strength measurements were made in the tip and flank regions of the corrugated medium.

Forming losses are reduced by increased wet pressing with a greater improvement in the flank than the tip region of the flute. A small reduction in tip forming losses is found, for a given furnish when a film forming latex is used. However, a greater reduction is evident when a non-film forming latex is employed.

Forming loss measurements were also made on non-bonded and bonded laminates. The non-bonded laminates resulted in much lower forming losses, while the heat-activated laminates resulted in large forming losses similar to those found with conventional medium.

These experiments suggest that forming losses can be reduced if cost-effective systems are designed which do not activate until the fluting process is complete.

INTRODUCTION

Forming and molding processes are commonly used on many materials including plastics, composites, wood, metals, and paper and board. Generally forming and molding processes are used to convert planar materials into two- or three-dimensional forms. In the paper and board industry these processes are used to produce such items as cups, plates, embossed patterns, and corrugated medium, the subject of this paper.

It is desirable to shape or form a material with minimal damage and loss of properties. Shape retention is another consideration, and this requires that the material be plastically deformed, with allowances being made for recovery and springback.

The set characteristics of paper and board and their relationship to forming and molding have been briefly discussed by Waterhouse [1]. This review was limited to in-plane tensile stresses; however, virtually no published work has appeared on the set characteristics of paper and board when subjected to more complex stress situations (i.e., both in-plane and out-of-plane stresses), and how they are affected by environmental effects such as temperature and moisture.

The manufacture of corrugated board is an essential step in the production of corrugated shipping containers. In single wall corrugated board, the fluted medium is glued between two linerboards. Critical to end-use performance of the corrugated container is its compressive strength characteristics, i.e., its edgewise compressive strength. This is the ability of the corrugated board to withstand compressive loads in a direction parallel to the flutes, i.e., its column strength, and normal to the surface of the linerboard, i.e., its resistance to flute failure (flat crush). In the first case, both the liner and medium's intrinsic compressive strength play a vital role, and the medium's

MD (machine direction) intrinsic compressive strength is vital to the board's flat crush performance.

In the fluting process, the medium is subjected to a complex stress situation which generally results in significant losses (forming losses) in medium properties, particularly MD compressive strength. (We will define forming losses shortly.) However, it is clear from the work of Sprague and Whitsitt [2] that different regions of the fluted medium suffer different losses in compressive strength, i.e., the bottom and top tip regions and the leading and trailing flank regions of the flute.

This investigation is concerned only with hot corrugating. Sprague and Whitsitt [2] have compared the forming losses of hot and cold corrugating. The effects of moisture and temperature are not clear since the interactions are quite complex. Increases in temperature may reduce the effective tension, relax internal stresses, alter plastic deformation behavior, and changing the equilibrium moisture content of the medium.

It nevertheless appears that hot corrugating will generally result in lower or equal forming losses when compared with cold corrugating.

Sprague and Whitsitt [2][3] have investigated the nature of forming losses, and demonstrated that bending stresses play an important role. It seems reasonable that the losses incurred during bending are primarily due to partial failure of the outer layers of the board when subjected to high levels of compressive strain during fluting. The nature of compressive failure in bending has been examined by Carlson [4]. The medium also undergoes significant compression during fluting, i.e., as much as 15% to 25% loss in caliper.

From simple bending theory, the strain in the outer layer of the board is given by $\epsilon = t/2R$ where R is the radius of the flute tip and t is board thickness. Therefore, a reduction in board caliper should result in a lower forming loss. Whitsitt and Baum [5] used wet pressing to reduce forming losses, which they expressed in terms of a retention ratio, i.e., the ratio of fluted to unfluted medium compressive strength. It was shown that the loss in compressive strength, i.e., one minus the retention ratio was proportional to caliper and the ratio of in-plane to out-to-plane longitudinal moduli raised to the one quarter power, and also inversely proportional to the radius of the fluting rolls.

The present investigation is, therefore, concerned with effects of densification by wet pressing, and synthetic fiber and binder addition on forming loss reduction. Densification by wet pressing is not only expected to improve the compressive strength of the medium, but also to reduce forming losses because of the reduction in caliper. Synthetic binder and fiber addition is employed to determine if the medium could be made more forgiving of the corrugating process, and what effect heat activation of the binder system during corrugating might have on forming losses.

EXPERIMENTAL PROCEDURES

Handsheets having a nominal grammage of 125 g/m2, and a non-random fiber orientation, were made on the Formette Dynamique. The furnishes used are given in Table I:

TABLE I. FIBER FURNISHES.

1. 100% NSSC Pulp C.S.F. 450 ml.
2. 92% NSSC Pulp/ 8% Kevlar pulp
3. 92% NSSC Pulp/ 8% 1/4" glass fiber

The sheets were pressed and dried on the IPST press-dryer to ensure little or no shrinkage. Low and medium levels of wet pressing were used. After pre-conditioning and conditioning according to TAPPI standards, nondestructive property measurements were made which included grammage, caliper, and in-plane and out-of-plane elastic constants using non-destructive techniques developed at the Institute of Paper Science and Technology [6][7].

The handsheets were then cut to produce MD and CD samples measuring 4"x 5", and were saturated with the latex binders given in Table II:

TABLE II. LATEX BINDERS.

A.	Carboxylated SBR	T_g = 42°C
D.	100% Styrene Latex	T_g = 105°C
F.	SBR 85% Styrene	T_g = 54°C

After saturation, the sheets were lightly blotted to remove excess surface latex, and then dried essentially at room temperature in the press-dryer at zero press load to again ensure that no shrinkage occurred. Control sheets were saturated in deionized water only. It was found that this procedure produced negligible changes in sheet properties, including compressive strength. The above properties were again measured after conditioning, and in addition, STFI compressive strength measurements were made.

A 1"x 5" sample was then heat treated at a temperature of 125°C and a nominal pressure of 7kPa for three minutes. An unheated portion of the sample was then fluted on a laboratory concora fluter (A flute) at a temperature of 177°C. The actual sample temperature was established to be 166°C using temperature sensitive crayons. STFI compressive strength measurements were then made at four points along the flute, i.e., the leading flank, upper tip, trailing flank and lower tip. Average forming losses for the tip and flank positions were calculated as the percent loss in compressive strength with respect to the uncorrugated heat treated samples.

RESULTS AND DISCUSSION

The elastic properties of the base handsheets are given in Table III. The addition of Kevlar pulp and glass fiber both reduce handsheet apparent density and elastic properties as expected. However, the loss in elastic properties is greater than if the reduction in density had been produced by a lower level of wet pressing.

It is also interesting to note that the in-plane anisotropy R is changed by wet pressing and non-wood fiber addition.

TABLE III. BASE SHEET ELASTIC PROPERTIES.

FURNISH	GRAMMAGE g/m^2	APPARENT DENSITY g/cm^3	IN-PLANE MODULUS mean $(km/sec)^2$	IN-PLANE ANISOTROPY R	OUT-OF-PLANE MODULUS $(km/sec)^2$
100% NSSC (low wet press)	127	0.523	6.39	2.89	0.163
100% NSSC (med. wet press)	118	0.752	7.78	2.42	0.217
92% NSSC 8% K. Pulp (low wet press)	132	0.467	5.36	2.77	0.127
92% NSSC 8% K. Pulp (med. wet press)	114	0.707	6.93	2.58	0.167
92% NSSC 8% 1/4" glass (med. wet press)	118	0.719	7.41	2.90	0.187

TABLE IV. MEAN SPECIFIC COMPRESSIVE STRENGTH Nm/g.

FURNISH	H_2O	LATEX A (Tg 42°C)	LATEX D (Tg 105°C)	LATEX F (Tg 54°C)
100% NSSC (low wet press)	17.2 (-)	25.9 (21.1)	22.2 (19.4)	25.7 (19.6)
100% NSSC (med wet press)	24.8 (22.1)	30.3 (24.7)	29.3 (24.3)	32.2 (24.4)
92% NSSC 8% K.Pulp (low wet press)	13.6 (-)	21.7 (17.5)	18.2 (15.5)	30.7 (23.3)
92% NSSC 8% K.Pulp (med wet press)	21.2 (19.7)	27.5 (21.1)	25.0 (20.2)	29.0 (20.5)
92% NSSC 8% 1/4" glass (med wet press)	21.9 (19.9)	30.1 (24.5)	26.6 (22.3)	31.2 (24.1)

The mean compressive strength of heat treated handsheets with latex addition are shown in Table IV. The values in parentheses are before heat treatment. Generally there is a significant improvement in compressive strength due to heating, part of which is due to a reduction in equilibrium moisture content. We note that wet pressing and latex addition improve compressive strength, and in the case of glass fiber addition, the level is equal to that of the control, i.e., 100% NSSC pulp for the film forming latexes A and F. In general, the 100% styrene latex D does not perform as well as the film forming latexes A and F even after heat activation. Latex D performs better with the 100% NSSC furnish than with either of the Kevlar pulp and glass fiber containing furnishes.

As described in the experimental section, flute tip and flank forming losses have been measured using the concora fluter as the corrugator. Results for the various furnishes are summarized in Table V.

TABLE V. TIP AND FLANK FORMING LOSSES * FOR VARIOUS FURNISHES.

LATEX	LOW WET PRESSING CALIPER mm	TIP %	FLANK %	MED. WET PRESSING CALIPER mm	TIP %	FLANK %
100% NSSC Furnish:						
H_2O	0.245	47	25	-	-	-
A	0.267	46	34	0.198	35	16
D	0.281	40	35	0.194	27	12
F	0.274	46	28	0.198	34	12
92% NSSC/8% Kevlar Pulp Furnish:						
H_2O	0.286	-	-	0.198	-	-
A	0.317	-	-	0.204	32	15
D	0.329	-	-	0.206	28	19
F	0.314	-	-	0.202	38	19
92% NSSC/8% 1/4"glass Furnish:						
H_2O	-	-	-	0.189	52	26
A	-	-	-	0.199	46	24
D	-	-	-	0.208	34	26
F	-	-	-	0.200	44	28

It is noted that forming losses are reduced by wet pressing as predicted above. The 100% styrene latex D also results in a lower forming loss for the tip region. Surprisingly, the flank losses are reduced more than the tip losses, i.e., 19% versus 12% as a result of densification by wet pressing. The flank region loss is probably due more to the effects of "calendering", although the medium in the flank region is subjected to bending strains in the labyrinth. Significant losses in in-plane and out-of-plane elastic properties with calendering have been reported by Charles and Waterhouse [8]. These authors also found a reduction in compressive strength with calendering, but not as great as expected from the reduction in elastic properties.

The effects of Kevlar pulp and glass fiber addition on forming losses are also given in Table V. We see that the glass-containing webs yields significantly higher forming losses. Furthermore, the tip losses for the glass fiber-containing webs are greater for the film forming latexes A and F. This suggests that fiber binder interaction was too well established prior to fluting and heat activation. This should not be the case with the 100% styrene binder D, where the forming losses are indeed lower.

In another set of experiments, we explored the effects of interlayer bonding and reinforcement on compressive strength and forming losses. Laminates were formed from paper having a grammage of 59.1 g/m^2 and photographic mounting tissue having a grammage of 66.1 g/m^2 (unbleached kraft paper impregnated with PVAc). Compressive strength and forming loss measurements were made on one, two-, and three-layers of paper, and then on two and three layers of paper with one layer of mounting tissue between each layer of paper.

Compressive strength measurements were also made on one, two - and three-layers of heat-activated mounting tissue.

The compressive strength and fluting loss measurements were made using the procedures described in the experimental section.

The results are summarized in Table VI. Note that the

TABLE VI. MD SPECIFIC COMPRESSIVE STRENGTH OF PAPER, PHOTOGRAPHIC MOUNTING TISSUE, AND PAPER/TISSUE LAMINATES.

LAYERS	PAPER Nm/g	1/t	MOUNTING Nm/g	TISSUE Nm/g*	1/t	LAMINATE Nm/g*	1/t
1	29.3	9.9	25.7	21.7	11.4	-	-
2	26.8	5.0	24.2	42.4	6.2	45.7	3.5
3	25.6	3.3	24.1	48.2	4.2	48.7	2.2

* heat activated

specific compressive strength of the paper decreases as the number of layers increases from one to three. This is expected since there is no bonding (i.e., no shear transmission) between the layers. We also note that two- and three-layers of paper give a span-to-caliper ratio 1/t falling within the plateau region for short span compressive strength measurements, i.e., between two and seven [9]. The photographic mounting tissues show a similar result before heat activation; however, after activation there is a large increase in compressive strength for both the two- and three-layer mounting tissues. Also when the two- and three-layer paper/mounting tissue laminates are heat activated a similar improvement in compressive strength is found.

Forming losses for the paper and laminate combinations are given in Table VII. For the layers of paper with no

TABLE VII. FORMING LOSSES FOR PAPER AND PAPER/PHOTOGRAPHIC MOUNTING TISSUE LAMINATES.

	PAPER ONLY			PAPER/P.M.T. LAMINATES		
LAYERS FLANK	CALIPER	TIP	FLANK	CALIPER	TIP	
	mm	%	%	mm	%	%
1	0.076	18.1	4.1	-	-	-
2	0.149	19.4	6.7	0.216	40.5	24.5
3	0.225	18.8	10.2	0.348	48.7	35.1

interlaminar bonding, we see that the tip forming loss is approximately constant while the flank loss, although at a much lower level, increases with the number of layers. Forming losses increase dramatically for both the two- and three-layer paper/photographic mounting tissue laminates. This possibly implies that the laminate is effectively bonded during the corrugating process and, therefore, does not allow the layers to slip as was presumably the case when the mounting tissues were absent.

If, as discussed above, bending is responsible for the tip forming losses, then these should be reduced as the caliper is reduced. In Figure 1 we have plotted the tip forming losses against caliper where we compare the 100% NSSC furnish results with those for the paper and paper/photographic mounting tissue laminates. It is suggested that forming losses be compared at constant caliper in order to make a fair comparison. We see that latex binder addition does produce some reduction in percentage tip forming losses, particularly latex D. The paper/photographic mounting tissue combination also gives a lower loss than the control (i.e., 100% NSSC furnish). The rate of reduction with decreasing caliper

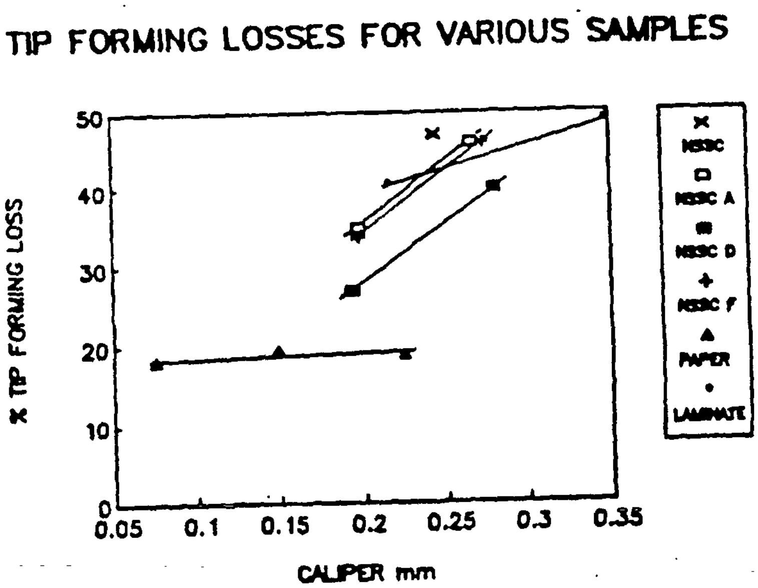

figure 1

of the laminate is presumably not as great as the NSSC furnish with binder addition, since the caliper reduction is not brought about by densification by wet pressing. The greatest percentage reduction in forming losses is achieved when there is no bonding between the layers.

CONCLUSIONS

Forming losses are reduced by increased wet pressing (confirming the findings of Whitsitt and Baum [5]), with a greater improvement in the flank than the tip region. When compared at constant caliper, film forming latex addition results in a small reduction in tip forming losses. However, a greater percentage reduction is found when a non-film forming latex is used.

The addition of Kevlar pulp does not significantly alter the level of forming losses when compared with the 100% NSSC furnish. On the other hand, the addition of glass fibers results in higher forming losses when compared with the 100% NSSC furnish. However, latex addition does reduce the forming losses of the glass-containing webs, particularly with the non-film forming latex. It is believed that other binder systems might be more effective with these furnishes.

Forming loss measurements were made on non-bonded and bonded laminates. The non-bonded laminates resulted in much lower forming losses as found by Sprague and Whitsitt [3], while the heat-activated laminates resulted in large forming losses similar to those found with conventional medium. It is presumed that the adhesive interlayer was too effective in shear transfer during the fluting process.

These model experiments suggest that forming losses can be reduced if cost-effective systems are designed which do not activate until the fluting process is complete.

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