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A LAYERED STRUCTURE OF PAPERBOARDS

Shin'ya Matsui^{*1}, *Minoru Kimura*^{*2}, and *Takashi Kadoya*^{*3}

Faculty of Agriculture, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113 Japan

ABSTRACT: A layered structure of the paperboards manufactured from two different consistency levels of pulp slurry was examined by measurement of the fiber orientation in the paper thickness direction. The standard deviation of the probability density distribution function of the fiber orientation in the paperboard made from 3.3% (high consistency) pulp slurry was found to be higher than that from 0.9% (low consistency) slurry. This indicates that the paperboard from a high consistency pulp suspension has rather a felt-like structure. The felt-like sheet structure of the high consistency paperboard was proved to be attributable to the core layer structure. The standard deviation of the function in the cross machine direction in all of the paperboards tested was higher than that in the machine direction. This implies the existence of microstriation in the papers which was probably introduced during the drying process.

1. INTRODUCTION

Various ways of evaluating sheet structure are pertinent in discussing the physical or mechanical properties of paper based upon sheet geometry[1,2]. The Mark and Perkins group has done pioneering work on development of a methodology for determining geometrical properties of paper by digitizing the photomicrographs of cross sectioned paper and the image of dyed fiber projected onto a measuring plate. They measured the inplane fiber orientation[3], as well as sheet geometry in the cross section including the aspect ratio, relative bonded area, moment of inertia of fibers in the paper[4,5], and the mass distribution along thickness direction[6]. Sheet structure related to its optical properties was measured by Hasuike and Murakami[7].

A fiber network is formed on the wire part of a paper machine after draining off a huge amount of water. Flocculation formed in the pulp suspension may remain in the network structure and influence the drainage and the retention of fines and additives. The fibers in a finished paper made from usual dilute

suspension, less than 2% consistency, are laid down almost parallel to the paper's plane. However, the thickening (a felt-like structure) of the wet mat can be observed when the stock consistency is more than 10%, which is much higher than actual fiber concentration, according to Radvan et al.[8]. They suggested that intermediate slurry concentration between these two consistency values provides a mixed structure of the two constructions. Thus, the layered structure of paper may gradually change toward a felt-like (3-dimensional) configuration as the stock consistency increases.

Recent energy-saving trials through the high consistency paper manufacturing method[9,10] showed that paper with a mixed structure could be made. Compressive strength of box board or surface strength of printing paper, for example, is greatly affected by the fiber orientation in the thickness direction[11].

The purpose of this study was to develop an evaluation method for fiber orientation in the z-direction, and then to compare the results obtained from samples made at different stock consistencies.

2. EXPERIMENTAL

2.1 Samples

Three kinds of commercially available paperboards were used; the consistency of pulp suspension trans-

^{*1} Present address: Canon Corporation

^{*2} Present address: Printing Bureau, Ministry of Finance

^{*3} Present address: Faculty of Science, Kanagawa University

Table 1 Physical Properties of the Paperboards

	Sample A	Sample B	Sample C
Basis weight (g/m ²)	208.7	207.2	213.7
Thickness (μm)	250	239	282
Standard Deviation (μm)	5.00	6.02	11.97
Density (kg/m ³)	834.5	868.4	756.4

ferred into a headbox was 0.9% (Samples A and B) or 3.3% (Sample C). Physical properties of the boards are listed in Table 1. The thickness, basis weight and local sheet density variation profiles in machine direction of Samples A and C were shown in a previous paper[12]. All of these variations in the paperboard manufactured from the high consistency pulp suspension were larger than those from the low consistency suspension.

2.2 Preparation of Cross Section of the Boards

Each specimen cut to a size of 1.5 × 12 mm was embedded in epoxy resin after conditioning at 60 °C for 24 h. The rectangular specimens were cut out of 20 different spots so that their longer sides coincided with the machine direction (MD) or cross-machine direction (CD) (10 specimens of each). The epoxy resin was comprised of 7.0 part of EPOK 812 (epoxy equivalent 143), 3.0 part of MNA (methyl nadic anhydride), 5.3 part of DDSA (dodecenyl succinic anhydride), and 0.24 - 0.32 part of DMP-30 [tri-(dimethylaminomethyl) phenol], respectively. The sample cut to approximately 2 μm thickness was mounted on a slide glass and microscopically examined under polarized light. Enlarged prints of the three paperboards (magnification: × 250) made from black and white negatives were prepared for digitizing.

2.3 Measurement of Fiber Orientation

A digitizing system composed of a digitizer (Oscon Electric, A-11 type) and a personal computer (NEC, PC 9801) was used for this evaluation. The center line of a sheet plane in the cross sectional photomicrograph was determined as reported previously [6,13]. The entire three dimensional fiber network should be surveyed for detailed understanding of the layered structure of paperboards. The network structure can be observed by continuous sectioning of the embedded specimen in a certain direction. In this study, however, the fiber orientation was estimated

from a single sectioned photomicrograph to avoid this time consuming process. Only fibers on the photomicrographs with a cutting length of more than 100 μm were chosen for measurement. Since the fiber width was found to be within approximately 15 μm by the use of the profile projector, an orientation angle of the measured fibers to the sectioning direction (MD or CD) was within approximately 10°. In practice, a transparent plastic sheet on which parallel straight lines were drawn with 5 mm spacing (in real scale) was placed on the photomicrograph, and points where the chosen fibers and the lines met were digitized as shown in Fig. 1. The photographs were set on

Fig. 1. Schematic drawing of the sectioned paperboard and the rectangular lines drawn on polyvinyl chloride film. The center line is determined by the method described in Refs[6,12].

the digitizer so that the center line was perpendicular to the straight lines. When the fiber segment curled remarkably between two perpendicular lines on the plastic sheet, careful digitizing for a short distance was carried out along the curvature of the segments. The orientation of the segments to the center line was then obtained. The mean value and standard deviation of fiber distribution were calculated from the data measured on the digitizer, and the results were output on a printer and an x-y plotter.

2.4 Classification of Surface and Core Layers

The cross sections of a sheet were divided into ten layers on the photomicrograph by the eleven points of y_0 to y_{10} (see Fig. 2) given by Eq. 1 to determine whether there was a difference in fiber orientation distribution between the core and the surface layers,

$$y_i = b_2 + (b_1 - b_2)(1.1i - 0.5)/10 \quad (1)$$

where b_1 and b_2 are the y-coordinate of the top and bottom "surface lines" of the sheet cross section, de-

Fig. 2. Determination of the surface and the core layers. y_5 coincides with the center line shown in Fig. 1. b_1 and b_2 are the upper and lower surface lines drawn by the method described in Refs[6,12].

scribed in previous reports[6,13]. By the y coordinate of the first digitizing point of the selected fibers, these fibers are automatically sorted into one of the ten layers, that is, $y_{10} - y_9, y_9 - y_8, \dots, y_1 - y_0$. The y coordinate of the first digitizing point in all of the fibers was located between $b_2 + 1.05(b_1 - b_2)$ and $b_2 - 0.05(b_1 - b_2)$, that is, between y_{10} and y_0 in Fig. 2, even if the papers had a rough surface.

2.5 Measurement of Paper Thickness

The linear variable differential transducer (LVDT) method was adopted. Details were described elsewhere[14].

3. RESULTS AND DISCUSSION

The computational results of the mean value of the fiber orientational angle and the standard deviation in the three samples are listed in Table 2. The mean

Table 2 Statistical Calculation of the Distribution Function in the Paperboards

	Sample A	Sample B	Sample C
Mean Value (°)	0.1	0.0	-0.8
Standard Deviation (°)	11.53	11.09	14.99

orientational angle of the three samples is situated around 0 degree. Fig. 3 shows the orientational distribution profile of the three samples, zero degree in this figure corresponding to the direction of the center line. From these results the fiber orientational profile in Sample C seems to be different from those in Samples A and B. The standard deviation of the

Fig. 3. Probability density distribution profile of Samples A, B, and C. Zero degree coincides with direction of the center line.

orientation angle listed in Table 1 was 15° for Sample C and approximately 11° for Samples A and B, indicating that Sample C has a transitional form from a layered to a felt-like structure. The orientational distribution of Sample C may therefore imply the presence of a marked fiber entanglement or flocculation in its high consistency pulp suspension. However, a further remarkable felt-like structure in a sheet from higher consistency stock would not be expected. Because the thickness of the wet mat is considerably reduced by hydraulic force in the wire part and subsequent pressure at the wet press nips and the calender roll nips in the subsequent papermaking process, the pulp fibers with a felt-like structure may become re-conformed in parallel to both paper surfaces after having gone through the press and the calender sections of the paper machine.

A more detailed analysis of the fiber orientation was then carried out. The cross sectional photomicrographs were divided into 10 layers and classified into two parts, 6/10 of the total thickness from both surfaces and 4/10 of the other core layers. The fiber orientation in the surface and the core layers in Sample A is shown in Fig. 4, and indicates that the orientational aspect of the two layers was almost the same. The measurement of Sample B gave a similar result. Fig. 5 shows the fiber orientation distribution in the surface and core layers of Sample C, and indicates the broadened fiber distribution still remains in the core layer even after passing through the caliper reducing process. The transitional felt-like orientation of Sam-

Fig. 4. Probability density distribution profile of the surface (S) and the core (C) layers in Sample A.

Fig. 6. Probability density distribution profile of MD and CD in Sample A.

Fig. 5. Probability density distribution profile of the surface (S) and the core (C) layers in Sample C.

Fig. 7. Probability density distribution profile of MD and CD in Sample C.

Table 3 Statistical Calculation of the Distribution Function of MD and CD in the Paperboards

	Sample A		Sample B		Sample C	
	MD	CD	MD	CD	MD	CD
Average Thickness (LVDT Method) (μm)	250	250	238	239	286	279
Standard Deviation (μm)	4.94	5.07	5.81	6.23	10.38	13.56
Mean Value ($^{\circ}$)	0.2	-0.1	0.0	0.0	-1.2	-0.4
Standard Deviation ($^{\circ}$)	10.73	12.63	10.05	12.48	13.73	16.54

ple C in Fig. 3 is, therefore, attributable to the core's fiber orientation.

Difference in the orientational distribution between MD and CD were then examined. In all specimens, the standard deviation of local thickness variation in CD, measured by the linear variable differential transducer method[12], was higher than that of MD, although the average thickness in the two directions was almost the same, as listed in Table 3. And the standard deviation of the probability density distribution

function in the fiber orientation profile in CD was also higher than that in MD in these three paperboards. Figs. 6 and 7 indicate the results of the distribution function of Samples A and C. These results would be attributable to the lateral shrinkage of the wet web during the drying process on the paper machine.

Paper made from high consistency slurry was reported to have remarkably high resistance against interlayer peeling[9,10]. The peeling resistance of the

high consistency pulp sheet (the same sheet as Sample C) was approximately twice as high as the conventional paperboards (Samples A and B). This distinction was anomalous, judging from a rather small difference in fiber orientational distribution between the samples made from the two different slurry consistencies. But it may be an evidence that the fiber entanglement introduced in high consistency slurry still remains even in a dry sheet after change in the fiber conformation by a remarkable reduction of its thickness due to hydraulic and nip pressure in the paper machine. Table 4 shows that the elongational strength

to undergoing the paper machine process may play an important role in the tensile strength of paper.

4. CONCLUSION

The layered structure of the paperboard manufactured from high (3.3%) and low (0.9%) stock consistency pulp slurry was studied through sectioned microphotographs. The probability density distribution function of the fiber orientation in the high consistency paperboard was found to be slightly broader than that in the conventional consistency paperboards. A considerable reduction of thickness of wet web took place through hydraulic force and subsequent pressing at the wet press nips and the calendered rolls, and then the fibers were reformed in the direction parallel to the paper surface. Therefore, no pronounced felt-like structure was observed.

The fiber orientation distribution function of the core layer was much broader than that of the surface layers in high consistency paperboards, although the distribution profile of the two layers was almost the same in low consistency board. Furthermore, in all three boards, the standard deviation of the function in CD was greater than that of MD, which is attributable to the existence of a microstriation parallel in MD introduced during drying in the paper making machine.

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Table 4 Mechanical Properties of the Paperboards

		Strain-to- failure (%)	Elongational strength (Nm/g)	Young's modulus (GPa)	Taeber stiffness (mN·m)
Sample A	MD	2.80	62.6	5.5	113
	CD	6.27	35.7	2.8	86
Sample B	MD	2.20	56.4	4.8	115
	CD	5.38	34.4	2.9	89
Sample C	MD	0.84	24.2	3.3	119
	CD	1.36	14.7	2.9	98

According to the results of the internal bonding strength measurement using the same three paper boards as this study done by Nomura[9], the Scott internal bond strength of the higher consistency board was approximately twice that of the lower consistency boards. The new surfaces of the higher consistency board created by the test was more fuzzy than that of the lower consistency boards.

of the high consistency paperboard was less than half the value of the paperboards made by the conventional slurry concentration. It was also reported that a poor formation sheet from unbleached softwood kraft pulp had distinctly reduced tensile strength compared with a normal formation sheet[15]. On the other hand, there was reported of a result that the tensile strength of a poor formation sheet from bleached softwood kraft pulp was only slightly less than that of a good formation sheet[16]. The reason for the severe decrease in the elongational strength in Sample C cannot be explained by the results of fiber orientation profile obtained in this study. Entanglement among the flocks formed in a high consistency slurry prior

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