Systematic Study of Paper Breaks in Papermaking Process Using Fracture Mechanics – (1) Evaluation of Fracture Toughness in Wet State

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SUMMARY

Fracture toughness was considered as one of the good estimates of the paper break tendency of paper web in the press room. Paper break on the paper machine is caused by many factors such as paper machine irregular vibrations, impurities in the fiber furnish, shives, and so on. On the paper machine, the solid content of paper web is changing very rapidly from less than 1% to over 95%. We tried to measure the fracture toughness of paper web at different solid contents for providing the fundamental knowledge of paper break. Stretches of wet web were also measured and compared to the fracture toughness changes. Four different fiber furnishes (SwBKP, HwBKP, ONP, and OCC) were refined to different degrees, and at different solid contents (40%, 60%, 80%, and 95%), their fracture toughnesses were measured. Two fracture toughness measurement methods (essential work of fracture and Tryding's load-widening method) were used, and we found they gave identical results. The stretch curves of the wet webs against the axis of solid contents were very similar to the fracture toughness curves of those.

Key words : Fracture toughness, Solid contents, Wet web, Stretch, Essential work of fracture, Load-widening, Tension, Paper machine, Paper break

INTRODUCTION

Frequent paper breaks in the middle of paper manufacturing process are the worst possible nightmare to the papermakers. Loss of productivity, energy, raw materials, and manpower are expected. A large amount of under-spec paper products, which were produced after the paper break, should be handled properly in order that they shouldn't go to the customers. However, papermakers can not avoid paper breaks. What they can do is just reducing its frequency. The paper breaks in the paper machine usually come from three places: wet web pick-up roll at the end of wire, between the last wet press stack and the dryer section, and after the surface size press. Three places have special characteristics in common. Paper web in those three places has high moisture content, significant amount of loading in the machine direction, and abrupt change of running angle.

Papermakers already knew those places, and installed special devices and applied special technologies for the prevention of paper breaks. However, there are still paper breaks and large economic losses in paper mills. We need to know how much the wet web is susceptible to break in those places for better understanding of the paper breaks. The paper break influencing factors are solid contents of the web, fiber types (mechanical pulp or chemical pulp, softwood or hardwood), refining degree, paper machine speed, wire type, wet press type, size press type, web tension, and so on. We picked up the first three factors (web solid contents, fiber type, refining degree) in this study. The others mostly come from paper machine itself, which is difficult and expensive to change. The first three factors, we chose, are surely related to paper machine type, too; however there are some rooms to be controlled by the operators.

In this study, we will measure fracture toughness of paper web under the different solid contents, fiber types, and refining degrees. Fracture toughness is not directly related to paper break, but until now, it is the best indicator ever known in this field. The measurement of fracture toughness is not easy at all even in even these days (1-9). Paper is a nonlinear viscoelastic material and its load-elongation curve forms a curve with initial rise of straight line. Therefore linear elastic fracture mechanics is not applicable, but elastic-plastic fracture mechanics should be applied. In paper mechanics, J integral and essential work of fracture, which are applicable to nonlinear elastic materials, are used to estimate fracture toughness (10-15). Recently, Tryding used load-widening curve in tension test, and obtained a fracture energy value per one test specimen (16). We will use both of the essential work of fracture (4-7) and the load-widening curve technique to estimate fracture energy and fracture toughness.

MATERIALS AND METHODS

We used SwBKP, HwBKP, OCC, and old newsprint fibers and applied different refining times to the fibers. The solid contents of wet paper web were controlled by changing drying time. We made handsheets in the Williams handsheet machine. After applying the same wet pressing intensity and sequence, we varied the drying time of the wet webs and sampled small pieces to measure their solid contents. We kept the solid content of the wet web until finishing all the physical testing. The wet web dried to the predetermined solid content, was put into the first vinyl folder and sealed. The wet web packed in the first vinyl folder was packed again in the second vinyl folder, and sealed. The double-time packed wet web was kept in the refrigerator. We checked the solid contents of the sample after 3 weeks in the refrigerator, and no significant changes were noticed.

When testing the samples, we brought the sample still in the vinyl folder, and cut the sample to the desired shape with the vinyl still attached. After the sample was securely connected between the grips in the Instron, we removed the vinyl attached to the test sample, and ran the test. After the test, we measured the weight of the sample, and checked its solid contents. We found no statistical differences in the solid contents of the samples before and after the test.

The measuring procedure of the essential work of fracture is simple and well known. We use deep double-edge notched tension specimens (DENT) containing varying ligament lengths (L) as shown in Figs.1 and 2 (4,5).

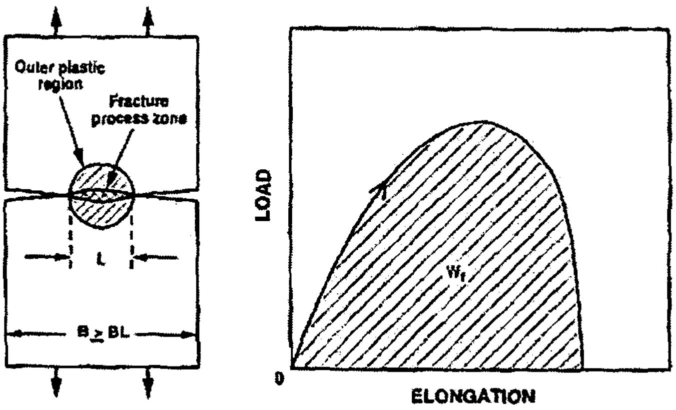

Figure 1. Schematic of measuring the essential work of fracture (from ref. 4,5)

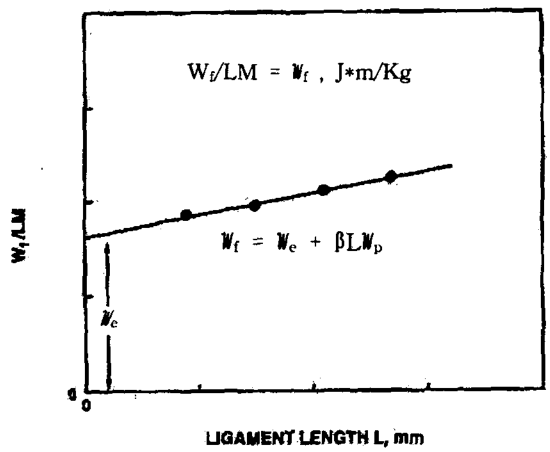

Figure 2. Measurement of essential work of fracture (W_e, from ref. 4,5)

In the measurement of the essential work of fracture of sample paper, we make paper test specimen as shown in Fig. 1, where we can find a DENT specimen with B≥3L (B : sample width, L : ligament length). In Fig. 2, as the ligament length of the specimen changes, W_f (total strain energy of the specimen) changes. The intercept of the line is called the essential work of fracture. It was well established that W_e is a good estimate of the fracture toughness of the material independent with specimen size and shape.

Another way of measuring fracture toughness is based on the analysis of stress-widening curve at the stable fracture region suggested by Tryding. In the stress-widening method, the specimen dimension should be controlled in such a way that the specimen fail at stable fracture region. We can see a stable fracture and immediate unstable fracture in Fig. 3. To make sure that the fracture occurs at the stable fracture region, one should found appropriate length-to-width ratio of the specimen before the fracture toughness test. How to select the ratio is well described in the reference . Usually, at very low length to width ratio, stable fracture occurs. One specimen can give one fracture toughness value in this method.

RESULTS AND DISCUSSIONS

Four different fibers furnishes were used to investigate the change of fracture toughness at different solid contents and at different refining levels. Their densities, breaking lengths, fracture toughnesses, and stretches were shown in Table 1. In handsheet making process, we applied a light wet pressing, and controlled the solid contents of the handsheets by varying drying time. The densities of the handsheets came out low side, compared to those of the handsheets made by TAPPI standard handsheet making process.

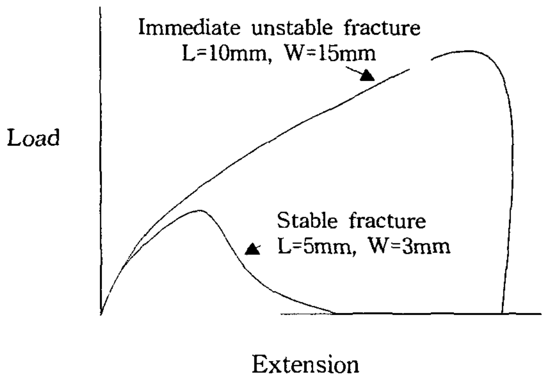

Figure 3. Example of stable and immediate fracture for the sack kraft paper specimen (16)

					40%	60%	80%	95%	40%	60%	80%	95%
Sample	Refining	Density	BL	Stretch	Solid contents,%				Solid contents,%			
	Minutes	g/cc	Km	%	Essential work of fracture, Jm/Kg				Tryding fracture toughness, Jm/Kg			
Softwood	30	0.52	8.30	3.93	7.93	25.77	32.22	60.2	3.8	33.89	54.2	44.3
	50	0.65	9.07	3.30	12.6	45.3	71.3	59.5	4.45	29.8	62.13	39.9
	70	0.70	8.69	4.95	11.76	44.35	67.8	63.8	4.84	60.44	65.16	44.3
Hardwood	15	0.54	2.41	0.92	3.18	3.13	8.4	8.73	0.63	2.1	4.53	5.74
	30	0.57	4.50	2.23	1.38	7.65	13.5	12.4	0.79	5.39	7.4	8.46
	45	0.65	5.75	2.27	3.67	6.00	22.13	18.0	0.77	7.25	16.5	11.61
Old newspaper	10	0.50	5.07	2.43	4.2	10.68	27.1	29.2	2.19	7.23	25.1	17.5
	20	0.43	5.54	1.90	4.43	12.27	27.13	22.33	2.99	9.94	21.85	18.2
OCC	20	0.61	4.88	2.25	3.65	9.53	28.8	25.2	1.34	9.83	14.98	11.22
	30	0.65	5.46	1.90	5.6	7.07	21.2	20.8	2.48	8.82	22.64	15.33

Table 1. Physical properties of the handsheets ($100g/m^2$). BL: breaking length

In Table 1, fracture toughnesses of softwood furnish were much higher than those of the other furnishes. We think that is because the softwood fibers are longer than the other fibers and the paper containing long fibers are difficult to break apart. Hardwood virgin fibers gave lowest fracture toughnesses at all solid contents levels. Even the old newspaper furnish gave higher fracture toughnesses than the hardwood virgin bleached chemical pulp fibers did. The OCC usually had long fibers in it and it did not surprise us to give higher fracture toughness than the hardwood furnish did.

The curves of fracture toughnesses, breaking lengths, and stretches of four different furnishes at 40, 60, 80, and 95% solid contents were shown in Figs. 4-7. In Figures, we could find that the test values of essential work of fracture were very similar to those of the fracture toughness measured by Tryding's method (load-widening method). Figure 8 showed their relationship (R^2 = 0.838). However, Tryding's method was very easy to perform, and gave stable test values everytime. In Tryding's method, it needed only one sample for obtaining one fracture toughness value. However, in the essential work of fracture, it needed four tests for obtaining one test value in our experiment. Furthermore, care should be taken in cutting the samples in four different ligament lengths. After all, the two methods gave almost identical trends of fracture toughness variation as the solid contents of the furnishes changed. Four different furnishes gave the same characteristic maxima of fracture toughness at 80% solid contents. Another interesting observation is that the stretches of four furnishes gave similar trends as the fracture toughnesses of those (initial rises and drops at 95% solid contents). In this experiment, we could say that the fracture toughness curve of the wet web was very similar to the stretch curve of it. If the fracture toughness is high in a certain solid content, we may expect the high stretch value of the wet web or vice versa.

The breaking length curves of the furnishes were totally different from those of the fracture toughness and the stretch. More refining of fibers only made higher breaking length of the wet web and dry web.

From the figures, we may recommend a strategy of protecting wet web from break. In wet state such as 40-60% solid contents, the breaking length of the wet web is extremely low, but its stretch is almost equivalent to the dry web. So, in low solid contents, the mechanism of carrying the web allowing no load but little extension should be used. In high solid contents, the mechanism of carrying the web allowing high load, but no large extension should be used.

CONCLUSIONS

We measured the fracture toughness of four different fiber furnishes at four different solid contents (40, 60, 80, and 95%), while varying refining times. Two different fracture toughness measurement methods, which were the essential work of fracture and the Tryding's load-widening method, were used in the measurement. We found two methods gave the same trends. A few other conclusions were made in the followings.

* The softwood BKP fibers gave the highest fracture toughness values at every solid content levels.
* The hardwood BKP fibers gave the lowest fracture toughness values, and even lower than the old newspaper fibers.
* The shapes of the fracture toughness curves at the axis of solid contents were very similar to those of the stretch curves. We think that there should be a positive relationship between the stretch and the fracture toughness of wet web.
* The two fracture toughness measurement methods of the essential work of fracture and the Tryding's load-widening method gave almost identical trends at the axis of wet web solid contents.

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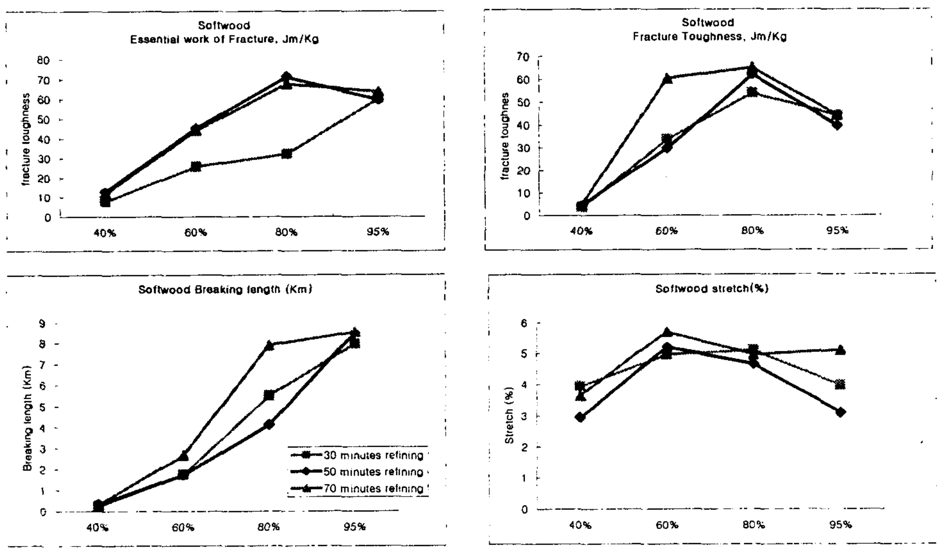

Figure 4. Fracture toughness, breaking length, and stretch of SwBKP

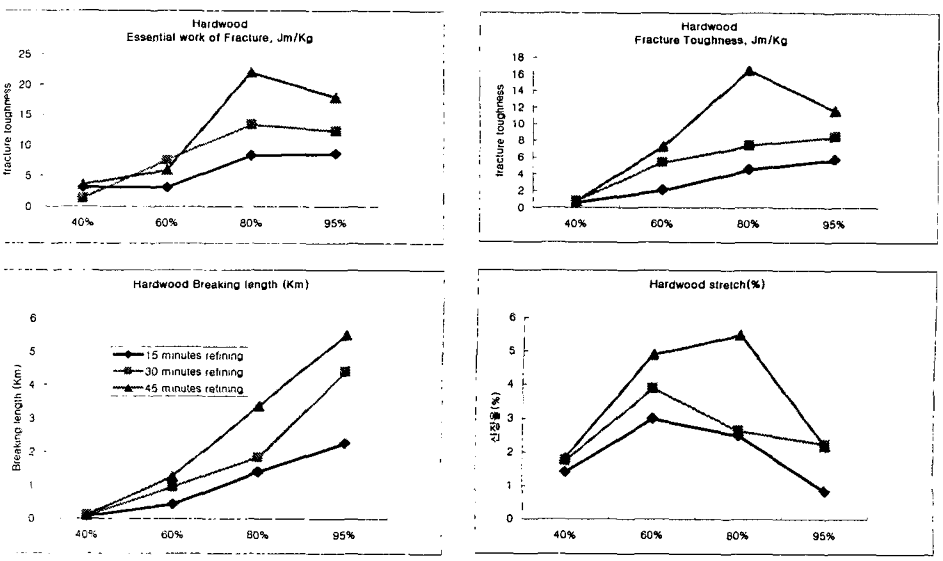

Figure 5. Fracture toughness, breaking length, and stretch of HwBKP

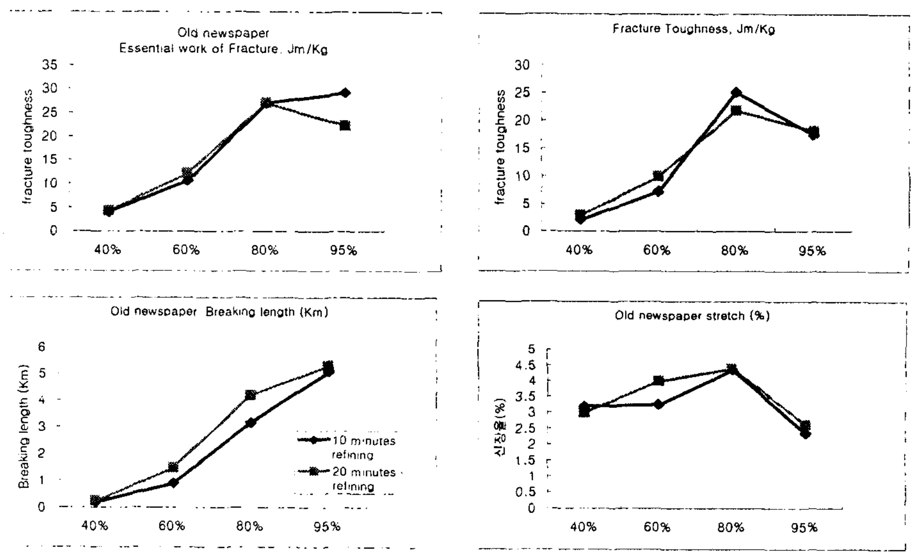

Figure 6. Fracture toughness, breaking length, and stretch of old newspaper

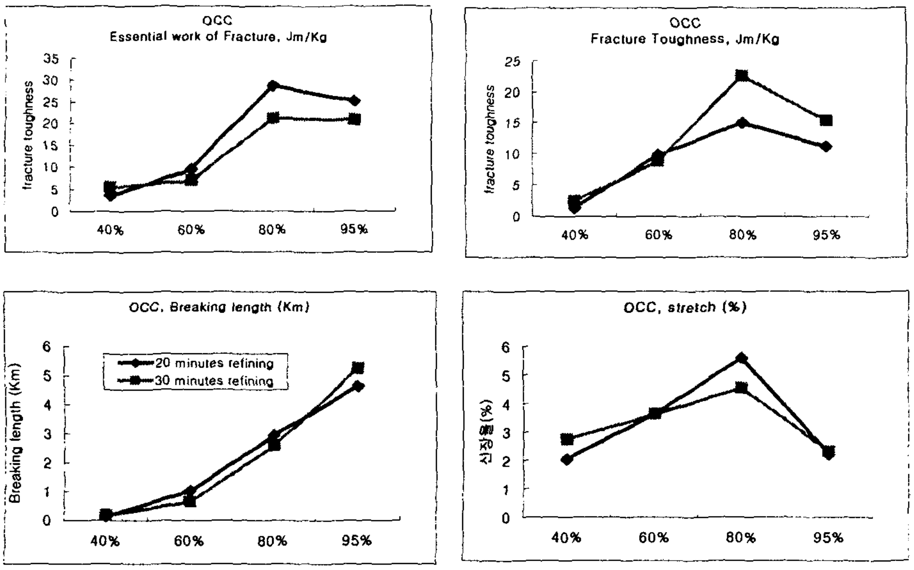

Figure 7. Fracture toughness, breaking length, and stretch of OCC

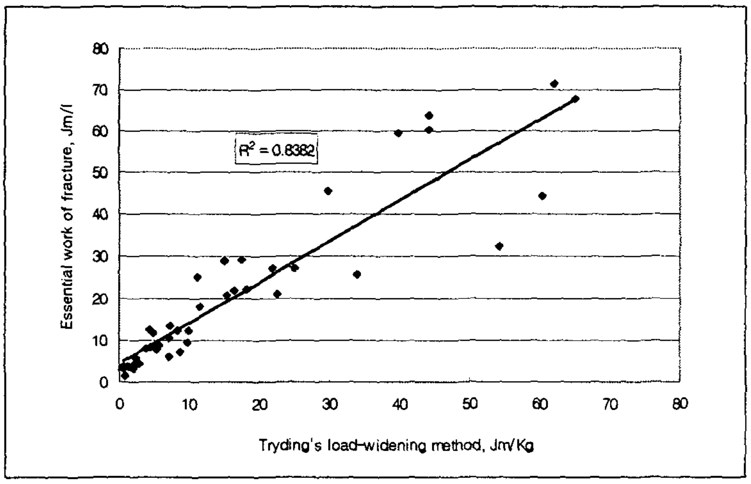

Figure 8. Relationship between the fracture toughness values measured by the essential work of fracture and Tryding's load-widening method