Fibre Treatment Uniformity in Pulp Refining

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Abstract: This paper explores implications of previous work which suggested that pulp refining is achieved by a small number of impacts. As a consequence, the purpose of multiple bar crossings in refiners is to expose many fibres to a few effective cycles, not to impose many cycles on each fibre. Based on this postulate, tensile strength increase was found to be well described by a cumulative probability equation having two parameters: (a) number of bar crossings and (b) probability of a successful refining outcome at each crossing. In this paper, this concept further with additional refiner data was explored and the link between the probability term and measurable refiner variables was examined. By proposing the possibility, these two parameters may be a desirable alternative to specific energy and specific edge load for characterizing refining action.

Keywords: pulp refining; refining uniformity; tensile strength; refining characterization

1 Introduction

Pulp refining is the key operation employed in a paper mill to enhance pulp quality. It can increase tensile strength of paper by a factor of three or more while at the same time reducing fibre length and tear strength. The action producing these changes in refiners has long been known to be non-uniform. However, the implication of this on paper properties is unclear. The objective of this paper is to review recent advances in our knowledge of refining uniformity and explore their implications, including a potential new approach to characterizing refining action.



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2 Previous studies

2.1 Sources of heterogeneity

There are many sources of non-uniformity (heterogeneity) in refining over a range of length scales. At the refiner scale, circulating flows produce different residence times

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of pulp in the refiner[1]. Pulp is unevenly impacted over the refiner radius due to non-uniform distribution of specific edge load (SEL)[2]. Within grooves, pulp may be poorly circulated[3] and even when well-circulated, has only a finite probability of being captured by a bar crossing[4]. During bar crossings, forces on flocs are not uniformly distributed among fibres[5].

Previous researchers have studied refining uniformity by staining fibres to reveal swelling caused by damage from impacts. They have shown that many fibres are not fully treated. For example, using a cupri(II) ethylendiamine dye, Eckhart et al[6] found that after refining to a tensile strength of 7 km in a pilot disc refiner, 30% of fibres had only 0~20% of their lengths swollen. They also showed distinct points of local deformation along fibre lengths where impacts appear to have taken place.

2.2 Forces causing refining

Fibres are flexibilized and surface fibrillated in refiners to increase their relative bonded area (RBA) and thereby increase tensile strength of paper. These effects are produced by bar crossings which impose forces to break molecular bonds in cell walls. A common view is that the process is one of fatigue weakening by repeated modest strain. However, this is questionable in light of the above evidence. Indeed, a study of fibre flexibilization by low amplitude flexing (3% of span), Tam Doo and Kerekes[7] showed that about 10,000 cycles were needed to reduce the stiffness of fibres by 50%. As shown later, this number of cycles far exceeds that in a typical refiner.

The possibility that only a few strong loading cycles produce refining was suggested in work on compression of single fibres by Dunford et al[8]. They showed that after the first few compression cycles, additional cycles added little to the state of the fibre, as shown in Fig.1.

In summary, evidence suggests that a few strong loading cycles on fibres produce the refining effect. This suggests an important conclusion: the main purpose of many bar crossings in refiners is to expose many fibres to a few effective cycles, not to impose many cycles on each fibre. In short, the role is to achieve uniformity of treatment.

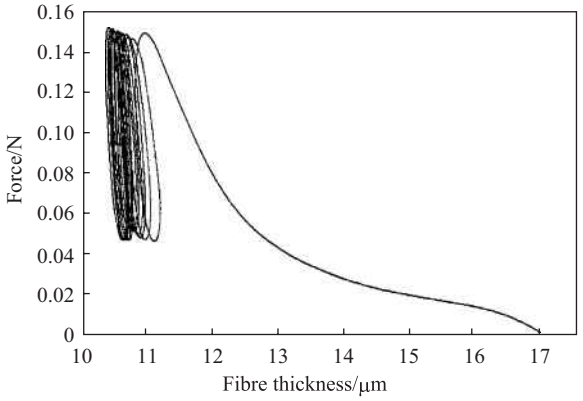


Fig.1 Compression of single pulp fibre showing that after first loading cycle, additional loading cycles have little effect on fibre response[8]

2.3 Compression refining

Compression refining is the simplest form of refining from the days of old when refiners were simply stamping mills. Accordingly, it is a good means to study refining heterogeneity on a lab scale. This was accomplished by Goosen et al[9] in a laboratory compression tester. They found that cyclic compression of a pulp pad produced no significant increase in tensile strength if the pulp was not redistributed between compression cycles. However, if redistribution took place between cycles, a significant increase in tensile strength took place with each successive cycle of compression. This suggested that the role of multiple cycles was to impose force on fibres that had not yet been impacted rather than multiple impacts on the same fibre.

Based on the above observations, tensile strength increase was modeled by a cumulative probability equation shown in Equation (1). Here, ΔT is the increase in tensile strength, ΔT_{max} is the maximum increase in tensile strength, P is the probability of a "successful refining event" expressed as a fraction, and N_B is the number of loading cycles imposed on the pulp.

$$\frac{\Delta T}{\Delta T_{max}} = 1-(1-P)^{N_B} \quad (1)$$

Equation (1) gave an excellent fit to the tensile

strength data. Probability P was found to have a value of P=0.06[9]. This means that 6% of the fibres were refined in each cycle, which means that a minimum of 25 cycles would be required to refine 100% of the fibres.

We define a "successful refining event" as one that produces a measureable increase in tensile strength by modifying part or all of a fibre. In compression refining, this effect is produced by compressive deformation and bending. In disc refining (discussed in next section), there is additional surface abrasion. In summary, we define a successful cycle by increase in tensile strength, not by a specific changes in fibre morphology, force on fibres, or energy expended on pulp.

2.4 Refiners

Heymer et al[10] explored the application of Equation (1) to disc and conical refiners. For N_B, they used the number of bar crossings a fibre would theoretically experience if it moved along a stator bar during its residence time in the refiner. In essence, this is the maximum number of impacts a fibre could experience. Variable N_B is readily calculated from Equation (2)[10]:

$$N_B = \frac{2BEL \cdot \omega \cdot D \cdot G}{Q} \quad (2)$$

Where:

BEL—Bar Edge Length, a plate factor supplied by vendors;

ω—rotational speed;

D, G—groove depth and groove width;

Q—volumetric flow through the refiner.

The actual number of impacts that a fibre experiences, N, is less than N_B because not all fibres are impacted at each bar crossing. For example, a simple mass balance suggests that only about 5%~10% of pulp in a typical groove can physically fit into a typical gap where it would be subjected to force[4].

Heymer et al[10] studied the effects of two refiners on strength increases of NBSK pulp. One was an Escher-Wyss laboratory conical refiner. The other was a 22 inch Beloit Double Disc pilot refiner with 5 different plates having: groove depths of 1~8 mm; groove widths of 2.5~12 mm; bar widths of 1~6 mm. In addition, the disc refiner was operated at pulp consistencies 1.5%~4.5% and *SEL* 0.07~8 J/m. Despite this wide range of conditions, Equation (1) was found to give a good fit to the data with an average of R^2=0.94. Values of P ranged from 0.12% to 6.7%, depending on the condition. These values are smaller than 6% obtained by Goosen[9], meaning less likelihood of fibres being successfully refined at each bar crossing. Interestingly, for a typical refining energy of E=120 kWh/t and a typical intensity range for this NBSK pulp of *SEL*=1~3 J/m, the average number of successful refining events was one, i.e. $P \cdot N_B \approx 1$. In short, as assumed, about one successful refining event took place.

Probability P differed for the differing plates, consistencies, and *SEL* levels. We now consider how P is linked to these factors with the aim of predicting it from measurable variables.

3 Theoretical estimate of *P*

Variable P is a combined probability of impact on pulp from a bar crossing and force exerted during this impact. Together these determine a "successful refining event". We may estimate probability of fibre capture to be proportional to fibre length, l, and inversely proportional to the pulp mass in the groove, m_G, from which the fibre is captured. This gives l/m_G. We next estimate intensity as force (F) per bar length, $F=SEL/s$, where s is the distance over a bar surface on which force is exerted. As described in Kerekes and Meltzer[11], for large bar widths, s is about a fibre length in size with some additional length to account for fibre stapling at the bar leading edge. In contrast, when bar width is smaller than a fibre length, bar width rather than fibre length determines s. These conditions can be summarized as:

$s=l+5Cl$ If bar width is larger than fibre length;

$s=W+5Cl$ If bar width is smaller than fibre length.

Where, s, bar width W, and fibre length l are in millimeters and C is consistency expressed as a fraction.

Combining the above, we propose a theoretical

estimate of P of the form:

$$P=k\frac{l \cdot SEL}{m_G \cdot s} \quad (3)$$

Where:

k—a constant;

SEL—Specific Edge Load, kJ/m;

l—fibre length, mm;

m_G—pulp mass in a groove along bar length, kg/m;

s—the distance over a bar surface on which force is exerted, mm.

4 Experimental evaluation

Two sets of tests were employed to evaluate Equation (3).

4.1 Test Set A

These data were selected from the findings of Heymer et al for conditions that excluded extremes not used for NBSK pulp, namely low (0.07 and 0.14 J/m) and high (8.0 J/m) levels of SEL. Initial fibre length was 2.3 mm. Values of P were obtained by fitting Equation (1) to tensile strengths over a range of N_B for each case. The results are shown in Table 1 with the calculated values of parameter: $\frac{l \cdot SEL}{m_G \cdot s}$.

4.2 Test Set B

A second set of tests was carried out recently using similar NBSK pulp in a 12 inch single disc laboratory refiner[11]. Various bar widths were tested with common groove dimensions of 6 mm depth and 4 mm width at a common consistency of 4.0%. Tensile strengths were measured over a range of energy and SEL. Equation (1) was fitted to these data as shown in Fig.2 for one of the plates.

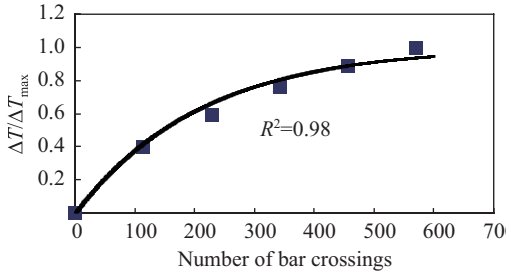


Fig.2 Tensile strength increase as a function of number of bar crossings, fitted to Equation (1) for case W=4.2 mm and SEL=2.1 J/m

The values of P with calculated values of parameter $\frac{l \cdot SEL}{m_G \cdot s}$ are shown in Table 2.

Table 2 Test Set B

W /mm	SEL /(J • m^{-1})	P /%	$\frac{l \cdot SEL}{m_G \cdot s}$ /(kJ • kg^{-1})
4.2	2.1	0.474	0.91
4.2	1.5	0.352	0.65
4.2	1.0	0.153	0.43
2.0	1.6	0.415	0.83
2.0	1.0	0.235	0.52

* Data from Kerekes and Meltzer[11].

Table 1 Test Set A

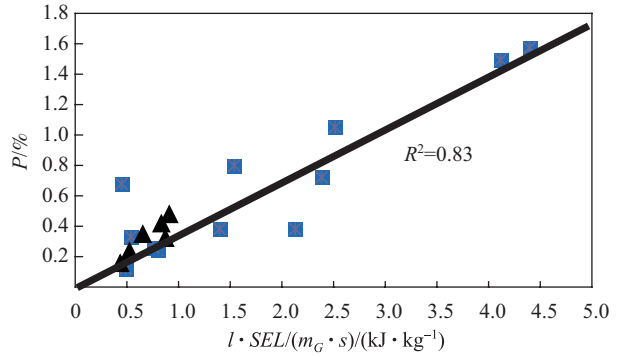
Type of refiner	Plate dimensions/mm			Consistency /%	SEL /(J • m^{-1})	P /%	$\frac{l \cdot SEL}{m_G \cdot s}$ /(kJ • kg^{-1})
	W	G	D				
Disc refiner	3.0	3.0	4.0	2.84	3.2	1.50	4.11
				4.55	3.2	0.72	2.39
				1.50	1.7	1.57	4.39
				2.50	1.7	1.05	2.52
				4.20	1.7	0.38	1.39
	2.5	2.5	5.0	4.20	2.7	0.38	2.13
				2.54	1.1	0.80	1.54
				4.50	1.1	0.24	0.80
Conical refiner	6.0	12.0	8.0	1.5	1.5	0.12	0.48
				3.0	3.0	0.68	0.45
				4.0	5.0	0.33	0.54
				3.0	5.0	0.26	0.75

* Data from Heymer et al[10].

5 Discussion

Fits of Equation (1) for Test Set B showed good fits similar to those reported for Test Set A, with an average R^2 of 0.98. Values of P from both sets of data fall in the same range, 0.1% to 1%. These are plotted against $\frac{l \cdot SEL}{m_G \cdot s}$ in Fig.3.

As shown in Fig.3, the correlation of R^2=0.83 is good given the broad range of test conditions examined and the numerous factors not accounted for, such as plate condition, method of calculating no-load power, pulp



* Square points are from Test Set A and triangular points are from Test Set B.

Fig.3 Plot of probability P against $l \cdot SEL/(m_G \cdot s)$ for the data in Tables 1 and 2

preparation before refining. The slope of the line gives a value of about k=0.35%/kJ/kg. In summary, this gives a first order approximation of P (in per cent) as shown in Equation (4).

$$P=0.35\frac{l \cdot SEL}{m_G \cdot s} \tag{4}$$

Clearly, further experimental work is required to verify this and determine the influence of additional refining variables on P.

6 Potential new approach to characterize pulp refining

We now consider the possibility of employing N_B and P as the basis for a new two-parameter characterization of refining. First, however, we consider conventional methods.

Pulp refining is typically characterized by two parameters, namely Specific Refining Energy, E, and Specific Edge Load, SEL. Although very useful, these parameters have shortcomings. They describe the amount and intensity of refining action in energy terms, but do not link these directly to a pulp property change. Furthermore, E and SEL are not independent of one another. They both depend directly on power.

Another two-parameter approach is based on number of impacts imposed on pulp, N, and intensity of each impact, I, where I is expressed as specific energy per impact on pulp (kJ/kg/impact). Thus, $E=N \cdot I$. This approach, however, requires an assumption of how much pulp is captured from a groove into a gap. One approach to estimate this is by the C-factor[12], but this has proven too complex for widespread use. Another approach is to consider the probability of fibre capture to be the ratio of fibre mass in the gap (m_T) to the mass in the groove from which capture takes place, m_G, where these are mass of pulp per unit bar length. Thus, $N=\frac{m_T}{m_G}N_B$. We may also express intensity in terms of energy per pulp mass in the gap, i.e. $I=\frac{SEL}{m_T}$. Thus,

$$E=N \cdot I\,\frac{N_B \cdot SEL}{m_G} \tag{5}$$

We may note here that Batchelor et al[13] have proposed using SEL and E/SEL as two independent parameters to describe refining. From Equation (5), it is apparent that the E/SEL is the total number of bar crossings per pulp mass per unit groove length, i.e.

$$\frac{E}{SEL}=\frac{N_B}{m_G} \tag{6}$$

In contrast to E and SEL, parameters N and P are independent of one another and are directly related to a pulp property of major interest in refining, tensile strength. They are linked directly to specific energy E for a special case. If P is small, as found in this study, Equation (1) can be expressed as a series expansion.

$$\frac{\Delta T}{\Delta T_{\max}}=N_B P-\frac{1}{2!}N_B(N_B-1)P^2+\cdots \tag{7}$$

This equation may be simplified when higher order terms can be ignored, i.e. when

$$\frac{1}{2!}N_B(N_B-1)P^2<<N_B P \tag{8}$$

which reduces to Equation (9) by when $N_B>>1$ and both sides are divided by $N_B P$:

$$N_B P<<2 \tag{9}$$

Under this condition, Equation (7) reduces to

$$\frac{\Delta T}{\Delta T_{\max}}=N_B P \tag{10}$$

If $l \approx s$ as is commonly the case, substituting Equation (3) for P, we obtain

$$\frac{\Delta T}{\Delta T_{\max}}=k\,\frac{N_B \cdot SEL}{m_G}=kE \tag{11}$$

This implies that tensile strength increases linearly

with specific energy E in the initial stages of refining. This is commonly observed in refining curves. We note here that Equation (11) is only valid only when P and N_B meet the condition defined by Equation (8).

7 Summary and conclusions

This study has provided additional support for an earlier finding that refining occurs from a few successful refining events on pulp and therefore the role of multiple bar crossings is to increase the probability of pulp experiencing these few events., i.e. overcome heterogeneity. A parameter to link the probability of a successful refining event during a bar crossing to a number of measureable refining variables was derived. It could be speculated that the two parameters in the cumulative probability equation for tensile strength increase could form the basis of a new approach to refiner characterization having advantages over the conventional approach of specific energy and specific edge load. Although further evidence is clearly required to support this postulate, it can be concluded that the approach has sufficient promise to warrant further study.

Acknowledgments

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