Gap mechanics in pulp refiners

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ABSTRACT: Studies of pulp refining have shown that a single bar impact on pulp has only a 1%–5% probability of producing a successful refining effect. This study has explored the reason why.

An analysis of refining kinetics suggested that small segments of a fiber length, about a fiber diameter in size, are treated during each impact. Measurements of localized swelling along fiber lengths caused by refining supported this finding. Based on these findings, it was postulated that force transmittal through fiber networks occurred primarily at fiber crossings. The small size of fiber diameters relative to fiber lengths accounts for the low probability of a successful refining event at each impact. This probability, and the probability of fibers being captured and impacted during passage through a refiner, account for the need for multiple bar crossings to refine pulps.

Application: This study provides researchers with new ideas on the fundamentals of pulp refining with the aim of spurring research on this important process.

Refining modifies pulp properties by imposing cyclic forces on fibers. Experiments on cyclic compression of single fibers have shown that the first cycle achieves most of the permanent strain and that subsequent cycles add little [1]. Later studies on compression of pulp pads showed that tensile strength increased only if the fiber network was redistributed between loading cycles. These findings suggested that the need in refiners is to expose new fibers to one successful loading, not repeated loading on the same fibers [2]. The latter case may be applicable for very small forces [3], but forces on fibers in refiners are substantial [4].

Based on the above scenario, Goosen et al. [2] developed a statistical equation for tensile strength increase based on two parameters: the number of impacts imposed on fibers, N, and the probability of a successful refining event at each impact, P:

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

In refiners, N is determined by cutting edge length (CEL) of plates, throughput flow, groove size, and fiber length, as described in [5]. On the other hand, P must be determined by fitting data to Eq. 1. Doing so for a range of refiners and pulps has shown P to be small, in the range 1%–4%. It was postulated in [5] that this was due to each impact affecting only a small increment of fiber length. The objective of this study is to explore this postulate and thereby cast light on the mechanics of refining, and in particular, to answer the question: why is P so small?

KINETIC MODEL OF THE REFINING PROCESS

We consider the manner in which forces act on fibers in a refiner gap. We do so by a kinetic model based on the picture proposed by Goosen et al. [2] that one effective force cycle creates a refining effect and that additional impacts on the same fiber have little effect. Although this implies treatment of entire fibers, it is likely that only parts of a fiber length are treated in any cycle. Thus, the refining process can be considered progressive fiber treatment along a fiber length to give a refined length, l_R, from the original length, l_O.

This model can be expressed in equation form as an incremental increase in refined fiber length, dl_R, governed by the incremental number of successful impacts on a fiber, dN_R. The latter is a function of incremental number of impacts imposed by bar crossings, dN, and the fraction of fiber length available to be refined, $\frac{l_O-l_R}{l_O}$, which gives:

$$dN_R = \frac{l_O-l_R}{l_O}dN \quad (2)$$

We note here that as refined length increases, the number of successful impacts, N_R, decreases, although the number of impacts imposed by bars, N, continues.

We next link dN_R to incremental increase in refined length, dl_R. We assume that force from each impact acts upon a length of size, w. Thus, for successful incremental impacts, the incremental increase in refined length is shown below:

$$dl_R = w dN_R \quad (3)$$

Combining Eq. 2 and Eq. 3, we obtain:

$$dl_R = \frac{w}{l_O}(l_O - l_R)dN \quad (4)$$

Integrating between limits $l = 0$ and $l = l_o$ gives:

$$\frac{l_R}{l_O} = 1 - exp(-\frac{w}{l_O}N) \quad (5)$$

P	N	$(1 - P)^N$	$exp(-PN)$	Δ
0.01	10	0.904	0.905	0.001
	100	0.366	0.367	0.001
	1000	4.3×10^{-5}	4.5×10^{-5}	2.0×10^{-6}
0.05	10	0.599	0.606	0.007
	100	0.00592	0.0067	0.00078
	1000	0	0	0

I. Values of Δ for the ranges studied.

LINK TO TENSILE STRENGTH INCREASE

We now compare Eq. 5 and the equation for tensile increase, Eq. 1. To do so, we postulate that:

$$P = \frac{w}{l_O} \quad (6)$$

Substituting Eq. 6 into Eq. 5 gives Eq. 5 and Eq. 1 in terms of P. We may compare them by determining the difference between them, Δ, as expressed below:

$$exp(-PN) - (1-P)^N = \Delta \quad (7)$$

Our range of interest is $0.01 < P < 0.05$ and $10 < N < 1000$ [5]. Values of Δ for this range are shown in **Table I**.

It is apparent that Δ is small in all cases. The largest difference is 0.007 when N is small and P is large, but even in this case, it is less than 1%. An alternative means of comparing Eq. 1 and Eq. 5 is by their ratio: $(1 - exp(-PN))/(1 - (1 - (1 - P)^N)$. This ranges from 1.00 to 1.018, giving a maximum difference of just under 2%. Accordingly, we may conclude that for practical purposes in our range of interest, Eq. 5 is equivalent to Eq. 1 and therefore:

$$\frac{l_R}{l_O} = \frac{\Delta T}{\Delta T_{MAX}} \quad (8)$$

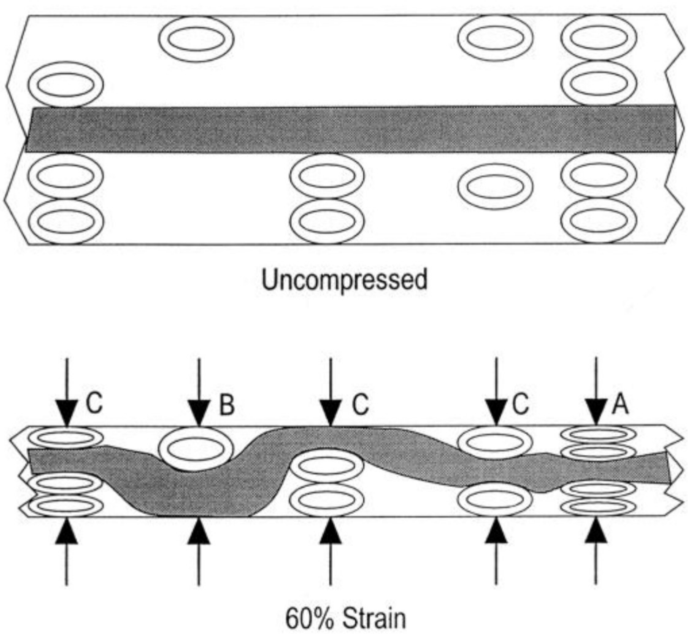
Thus, if postulate $P = w/l_0$ is correct, the fraction of fiber length refined equals the fraction of maximum tensile strength increase attained.

PHYSICAL SIZE OF *w*

We first estimate the size w from previous refining experiments reported in [5]. Here, P was found to be about 4% for both northern bleached softwood kraft pulp (NBSK; fiber length 2.5 mm, diameter 36 µm) and eucalyptus (fiber length 0.9 mm, diameter 16 µm). These give w = 100 µm and 36 µm respectively, about 3.3 and 2.3 fiber diameters. Thus, w appears to be a few fiber diameters in size.

This observation suggests that forces on fibers in networks act through fiber crossings, as illustrated in **Fig 1**. Fibers are compressed to differing levels, with some to the point of complete lumen collapse. Although few in number, these points bear a disproportionate fraction of the total load and cause a refining effect.

We next estimate the size of w from measurements on individual fibers. Forces imposed at points on fibers will produce distinct features. Such were observed by Eckhart



1. Illustration of compression at fiber contact points [6].

2. Fiber showing localized swelling totalling 36.4% of total length [7].

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et al. [7], who measured "fiber damage" caused by refining. They employed an acupri(II)ethylendiamin dying technique to swell fibers and then measured the fibers by transmitted light microscopy. Fiber images were analyzed by algorithms developed by Hirn [8] to determine the degree of local damage manifested as swelling along the length of each fiber.

An example image from their findings in [7] is shown in **Fig. 2**. This shows evidence of localized fiber swelling over short segments of about a fiber diameter in size. This is an example of balloon swelling, but volume swelling and gel swelling were also observed [7]. The image resolution does not provide a clear picture of these. Added together, these segments make up a "mean calculated damage," which in essence is the refined fiber length.

In summary, experimental evidence supports the creation of localized fiber swelling in zones of about a diameter in size along a fiber length. It is logical that tensile strength will increase as more of a fiber length becomes swollen, as postulated in our kinetic model. In the limit, maximum tensile strength would be reached when the entire fiber is swollen.

In closing, it should be noted that the evidence presented here does not definitively prove the validity of the model or the postulate. Doing so would require measurements of local swelling accompanied by measurements of tensile strength. Rather, what has been produced in this study is a logical and plausible picture of the refining process that is consistent with available experimental evidence. Clearly, there is a need for further study of this subject.

CONCLUSIONS

The findings of this study suggest an answer to the question posed at the beginning of this paper: why is the probability of a successful refining effect at each bar impact so small? The answer appears to be that forces are transmitted through fiber networks at points of fiber crossings. Given that fiber diameters are small relative to fiber lengths, only a small fraction of fiber lengths are treated during each bar impact. This probability and the probability of fibers being captured and impacted at each bar crossing govern the need for multiple bar crossings to refine pulp. **TJ**

ABOUT THE AUTHOR

My late colleague Dave McDonald and I published a series of papers on pulp refining over the years, the first two of which appeared in *TAPPI Journal* in 1991. In recent years, as we dug deeper into the mechanics of the process, we were puzzled over the low probability of producing successful refining effects on fibers in the gap of a single bar crossing. I returned to this question in recent months and came up with a plausible explanation, which I wanted to share with the pulp and paper community.

The most difficult aspect of this study was that it was necessary to link the refining process to the outcome of refining. This required the solution of a differential equation and comparison to a probability equation already published. Fortunately, only a limited range of conditions were relevant to this study. Over this range, a comparison could be made.

This research was aimed at a better understanding forces on fibers in pulp networks in pulp refiners. It has no immediate mill application, but the finding of limited force transmittal in refiner gaps may spur new efforts to improve the process.

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