The Role of Multiple Loading Cycles in Pulp Refiners

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KEYWORDS: Disc refiner, Low-consistency, Compression refining, Tensile strength, Number bar crossings

SUMMARY: This study compared findings from an industrial refiner to recent findings from cyclic compression of pulp mats which suggested that only a few suitable loading cycles were needed to produce pulp strength increase. The results from this study concur with those from the compression study over the normal range of refining intensity. This suggests that the main role of multiple loading cycles imposed on pulp by multiple bar crossings is to overcome heterogeneity, not to induce fatigue weakening.

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Introduction

In pulp refining, forces are applied to pulp in a cyclic manner to produce changes in fibre properties. The precise mechanism by which the forces do so is uncertain, but many investigators have attributed the action to fatigue weakening of fibres. These past views have been summarized in review papers by Page (1989) and Atack (1977). However, recent work by Goosen et al. (2007) has suggested another role of the cyclical application of forces in refining: redistribution of fibre networks between loading cycles to expose new fibres to forces. In short, the role is one of overcoming heterogeneity.

In a recent study of compression of pulp pads, Goosen et al. (2007) found that without fibre redistribution between loading cycles there was little tensile strength increase of pulp. However, when fibre networks were redistributed after each loading cycle, substantial strength increases were obtained. They proposed a model for this strength increase based on the observations of Dunford and Wild (2002) and Wild et al. (2006) that only a few cycles were needed to flexibilize single fibres, not thousands of cycles as is common in fatigue phenomena. Making the assumption that the refining result is produced by one successful loading cycle, Goosen et al. (2007) proposed a cumulative probability model for tensile strength increase. This model predicted the form of the observed increases in tensile strength very well when fibre networks were redistributed after each loading cycle.

The above finding for compression refining raises the question of whether the same holds true for industrial refiners. Specifically, is the role of multiple bar crossings in refiners one of overcoming heterogeneity of refining rather than imposing fatigue weakening. The objective of this paper is to answer this question.

Analysis

In Compression refining, an expression was derived by Goosen et al. (2007) that related tensile strength increase $\Delta T$ to the number of loading cycles imposed on the pulp pad, $N_c$ and the probability that each cycle was successful in creating a refining result, $P_c$. The result is given by the cumulative probability distribution below:

$$\Delta T = 1 - (1 - P_c)^{N_c}$$ (1)

The analogous expression for a pulp refiner is:

$$\Delta T = 1 - (1 - P_b)^{N_b}$$ (2)

Here $N_b$ is number of available bar crossings a fibre may experience during its passage through a refiner, and $P_b$ is the probability that each crossing inflicts a successful refining result.

The number of available bar crossings, $N_b$ is in essence the number of bar crossings seen by a point passing along the edge of a bar through the refiner. Thus, $N_b$ can be readily determined from the geometry and operating conditions in a refiner as shown in the Appendix, giving the expression below:

$$N_b = \frac{CEL \cdot D \cdot G}{Q}$$ (3)

Here $CEL$ is the cutting edge length, $D$ is the groove depth, $G$ is the groove width, and $Q$ is the volumetric flow rate of the suspension through the refiner. Further details are given in Appendix.

The probability $P_b$ is the likelihood of a successful refining result at each bar crossing. In refiners, this is a composite of the probability of capture of fibres in a groove and transport into the adjacent gap, and the
probability that once in the gap, pulp is subjected to a force of sufficient intensity to create a refining result.

**Experimental Program**

We evaluated equation (2) employing data obtained on a 22” Beloit Double Disc pilot refiner and an Escher-Wyss laboratory refiner. The trials examined five different plate patterns over a range of different energies and intensities shown in Table 2. The power cited is the net power. The consistencies are nominal values. The rotational speed for the double disc refiner was 900 rpm and for the Escher-Wyss refiner was 1000 rpm. The plate dimensions used are summarized in Table 1. The trials were conducted using a Northern bleached softwood kraft pulp.

<table>
<thead>
<tr>
<th>Plate</th>
<th>Bar Width [mm]</th>
<th>Groove Width [mm]</th>
<th>Groove Depth [mm]</th>
<th>Bar angle</th>
<th>CEL [km/s]</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>3.0</td>
<td>4.0</td>
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<tr>
<td>2</td>
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<td>2.5</td>
<td>5.0</td>
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<tr>
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<td>1.0</td>
<td>2.5</td>
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<td>4.0</td>
<td>21.5</td>
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</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>12.0</td>
<td>8.0</td>
<td>16.0</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Table 1: Summary of refiner plate geometries

Table 2: Summary of experimental trials from Olson et al. (2003) (** at 120 kWh/t)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Type</th>
<th>Plate</th>
<th>$C_p$ [%]</th>
<th>Power$_{net}$ [kW]</th>
<th>SEL [J/m]</th>
<th>$N_B$ [-]</th>
<th>$\Delta BL$ [km]</th>
<th>$P_B$ [%]</th>
<th>$P_B^* N_B^*$ [-]</th>
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<tr>
<td>A</td>
<td>A</td>
<td>1</td>
<td>2.84</td>
<td>65</td>
<td>3.25</td>
<td>94</td>
<td>6.2</td>
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<tr>
<td>B</td>
<td>A</td>
<td>1</td>
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<td>64</td>
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<td>1.07</td>
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<td>5.7</td>
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</tr>
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<td>55</td>
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<tr>
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<td>B</td>
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<td>3.00</td>
<td>1.4</td>
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<tr>
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<td>B</td>
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<td>B</td>
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<td>492</td>
<td>2.7</td>
<td>0.26</td>
<td>1.28</td>
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</table>

As is evident in Fig. 1, the fit is very good. The fits for the other 17 cases were similarly good, having an average $R^2 = 0.942$. The values of $P_B$ along with $N_B$ for each case are shown in Table 2.

The values of $P_B$ in Table 2 fall in the range 0.12 to 6.7%. This is smaller than previous findings. Goosen et al. (2007) found a value of $P_C \approx 6\%$ for compression refining of a pulp pad. In earlier work, Kerekes and Olson (2003) estimated upper limits of probability based on fibre capture. They estimated a 20% probability based on the zone in a groove from which fibres could be captured, and 5% based on the amount of fibre that could physically fit into a typical gap. The lower average values found in this study suggest that probability of a successful refining event at a bar crossing depends on more than capture probability.

The product of $P_B$ and $N_B$ represents the total number of successful refining events experienced by pulp on passage through a refiner. Values of $P_B^* N_B$ are shown in Table 2 and in Fig. 2. These data show that tensile strength increases with $P_B^* N_B$. Most important for this study, however, the values are mostly around one, i.e. $P_B^* N_B \approx 1$, for the normal range of intensity ($SEL = 1 - 3$ Ws/m$^3$). This supports the postulate stated earlier that only one or a few loading cycles are needed for refining. When SEL is very small, $P_B^* N_B$ must be much larger to compensate for the low

**Results and discussion**

The increases in tensile strength for the refining conditions tested are shown in Table 2. These data were fitted to equation (2) by regression analysis. An example of the fit of tensile strength ($AT$) development as a function of bar crossings $N_B$ is shown in Fig 1.

![Fig. 1: Tensile str. plotted against cumulative probability for $P_B = 0.72\%$](image-url)
forces in the gap. When $SEL$ is very large, even large values of $PB \cdot N_B$ fail produce substantial strength increase as is evident in Fig. 2. This is due to fibre shortening. The Length weighted average fibre length in this case was reduced from 2.30 mm (unrefined) to 1.34 mm at 120 kWh/t energy input as can be seen in Table 3.

![Figure 2: Increase in tensile strength as a function of total number of refining events experienced by pulp on passage through a refiner at differing levels of intensity](image)

Table 3: $l_{lw}$ average fibre length development at **120 kWh/t (unrefined = 2.30 mm)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Refiner</th>
<th>Plate</th>
<th>$C_F$ [%]</th>
<th>$SEL$ [J/m]</th>
<th>$l_{lw}$ [mm]</th>
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<td>2.05</td>
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<td>3.20</td>
<td>2.07</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>1.55</td>
<td>1.70</td>
<td>2.14</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>2.48</td>
<td>1.70</td>
<td>2.15</td>
</tr>
<tr>
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<td>1.70</td>
<td>2.22</td>
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<td>2.29</td>
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<td>2.54</td>
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<tr>
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<td>0.14</td>
<td>2.23</td>
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<td>4.40</td>
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<td>3.00</td>
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**Conclusions**

The findings of this study support the postulate that only one or a few loading cycles of appropriate intensity are required to create the refining effect of strength increase. The level of intensity must be sufficient to create this refining effect but not so excessive as to shorten fibres. Consequently, the role of many bar crossings in refiners is primarily one of exposing many fibres to a few loading cycles rather than imposing many loading cycles to create fatigue weakening. In short, the role is to overcome heterogeneity.

These results further suggest heterogeneity is governed by two factors: probability of capture and transport into gaps and probability of suitable forces applied in gaps. In a subsequent publication, we will explore using this combined probability with comminution analysis to measure refining heterogeneity from fibre length changes.

**Acknowledgement**

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**Literature**


**Appendix**

**Method for calculating \( N_B \)**

We consider here a conical and a disc refiner shown in Fig. A1 with plate dimension shown in Fig. A2.

**CONICAL REFINER**

**DISC REFINER**

The symbols \( S \) and \( R \) represent respectively for the stator and the rotor) and radii \( R_1 \) and \( R_2 \) represent the radii at the entry and exits of the working zones of refiners. Assuming rotor and stator have the same bar pattern and \( W = G \), the number of bars located on a circumference of radius \( r \) is given by:

\[
n(r) = \frac{2\pi r \cos \varphi}{(W + G) \sin(\alpha_{st})}
\]

(4)

Noting that \( \alpha_{st} = \pi / 2 \) for a disc refiner, the number of bars over the circumference having radius \( r \) is:

\[
n(r) = \frac{2\pi \cdot r \cos \varphi}{W + G}
\]

(5)

The number of bar crossings at radius having the latter expression, we should be able to compute the number of bar crossings seen by a point, \( N_B \) using:

\[
dN_B = n(r) \omega dt
\]

(6)

\[
dt = \frac{dr}{V(r)} = \frac{dr}{Q / A(r)} = \frac{A(r)}{Q} dr
\]

(7)

with

\[
A_s \approx 2\pi r \left( \frac{2 \cos \varphi \cdot D \cdot G}{W + G} \right)
\]

(8)

\[
\therefore dN_s = \frac{8 \cdot \pi^2 \cdot (\cos \varphi)^2 \cdot \omega \cdot D \cdot G}{(W + G)^2} \cdot r^2 dr
\]

(10)

After integration of equation (10) over the upper and lower boundary of \( R_2 \) and \( R_1 \) respectively, and substitution of equation (8) into (7) and we obtain:

\[
N_s = \frac{8 \cdot \pi^2 \cdot (\cos \varphi)^2 \cdot \omega \cdot D \cdot G}{(W + G)^2} \cdot \left( \frac{R_2^3 - R_1^3}{3} \right)
\]

(11)

A combination of many of the term in equation (11) gives what is defined at the Cutting Edge Length, CEL. Since values of CEL are commonly specified for refiner plates, a further simplification may be introduced by reexpressing (11) in terms of CEL.

An expression for CEL can be found in the technical literature (Technical Information Sheets 1995-1996, TAPPI Press, TIS 0508-05.) as:

\[
CEL = \sum_{i=1}^{n_s} n_s \cdot \omega \cdot dx
\]

(12)

If the rotation speed \( \omega \) is given in \([\text{rev/s}]\) and \( r \) in \([\text{m}]\), the previous calculation leads to the notion of \([\text{km cut per s}]\).

This is similar to an equation given by Kerekes et al. (1995) by the following formula:

\[
CEL = \int_{R_1}^{R_2} n_s(r) \cdot n_s(r) \cdot \omega \cdot dr
\]

(13)

Substituting equation (5) into (13) leads to:

\[
CEL = \int_{R_1}^{R_2} \frac{4 \cdot \pi^2 \cdot (\cos \varphi)^2 \cdot \omega}{(W_s + G_s) \cdot (W_s + G_s)} \cdot r^2 dr
\]

(14)

Both plates are supposed to have the same bar pattern since it relies on the industrial practice. After some calculations, an analytical expression of the cutting speed is obtained:

\[
CEL = \frac{4 \cdot \pi^2 \cdot (\cos \varphi)^2 \cdot \omega \cdot (R_2^3 - R_1^3)}{(W_s + G_s)^2}
\]

(15)
By comparing equation (15) with (11) we can conclude that:

\[ N_B = CEL \cdot \frac{2 \cdot D \cdot G}{Q} \]  \hspace{1cm} (16)

Danford (1969) suggested that the number of impacts was dependent on the residence time of the fibre in the refiner and the speed of the rotation of the rotor. Both are accounted for in our derivation.

---

**Nomenclature**

- \( A(r) \): Area for fibre flow located on a circumference of radius \( r \), [-]
- \( \Delta BL \): Breaking length increase of paper, [km]
- \( C_f \): Consistency pulp suspension, [%] or [-]
- \( CEL \): Cutting Edge Length, [km/s]
- \( D \): Groove Depth of the Rotor or Stator, [mm]
- \( G \): Groove width of the Rotor or Stator, [mm]
- \( l_{lw} \): Average length weighted fibre length, [mm]
- \( n(r) \): Number of bars located on a circumference of radius \( r \), [-]
- \( N_B \): Number of bar crossings fibre experiences while traveling thr. refiner, [-]
- \( N_C \): Number of compression cycles, [-]
- \( P_B \): Probability that each bar crossing was successful in creating a ref. result, [-]
- \( P_C \): Probability that each cycle was successful in creating a refining result, [-]
- \( Power_{net} \): Applied net power [kW]
- \( Q \): Volume throughput, [m³/s]
- \( r \): Radius, [m]
- \( R_1 \): Inner radius refiner, [m]
- \( R_2 \): Outer radius refiner, [m]
- \( SEL \): Specific Edge Load, [Ws/m] or [J/m]
- \( t \): Time, [s]
- \( \Delta T \): Tensile strength increase, [-]
- \( V(r) \): Volume for fibre flow located on a circumference of radius \( r \), [-]
- \( W \): Bar Width of the Rotor or Stator, [mm]
- \( \alpha_{RS} \): Angle between rotor and stator, [-]
- \( \phi \): Bar angle, [°]
- \( \omega \): Rotational speed, [rev/min] or [rev/s]