Effect of bar edge conditions on fibre trapping in low consistency refining

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Abstract

In a low consistency refiner pulp fibres are trapped between the bar edges of the rotor and stator and worked into the narrow gap between rotor and stator. No refining occurs if the fibres are not trapped. A reduction in fibre trapping is believed to be in the common observation that refining becomes less efficient as the bars wear and lose their sharpness.

This paper examines the effect of bar edge sharpness on relative fibre trapping in low consistency refining. The measurements were made on a bleached softwood kraft pulp at consistencies ranging from 1–6% using a conical laboratory refiner. Three sets of trials were done. One set of trials was done with a set fillings that had been worn in number of previous refining trials, while a second set of trials were done with a set of fillings where the bar edge had been sharpened by running the refiner with quartz sand. A third set of trials was done with fillings in which the bar edges had been manually rounded with abrasive paper.

The results showed that the fraction of the refiner bar length that trapped fibres was approximately proportional to pulp consistency for all three trials, independent of bar edge sharpness. The reduction in fibre trapping, with lower consistency, increases the harshness of the refining on the fibres, at a given level of refining power. The results also showed that the artificially treated bars trapped generally had a lower fraction of the bar surface trapping fibres, which also increased the harshness of the refining process. .

Introduction

Low consistency refining is the principal treatment for improving the mechanical properties of paper made from chemical pulps. A pulp refiner changes fibre cell wall structure by trapping fibre mats between rotor and stator bars and mechanically treating the fibres by cyclic strain of high frequency. It is known that three separate forces are imposed by refiner bars on the fibres *(1-3)*: a corner force exerted at the edges of the bars; a normal force compressing the fibre mat and a shear force generated by the bar surface moving over the compressed mat of fibres. The presence of fibres on refiner bars is a prerequisite for application of this old technology as only those fibres trapped between the bars are treated.

Refiner action is usually characterised by the Specific Energy Consumption (SEC), which is the energy per unit mass of pulp and a measure of refining extent. The most commonly used measure of refining intensity is the Specific Edge Load (SEL)-the energy consumed when a unit length of rotor bar crosses over a unit length of stator bar *(4)*. The refiner cannot apply forces on the fibres and change their structure if the fibres are not trapped between bar surfaces. No energy will be consumed where sections of rotor and stator bar cross unless a fibre mat is being trapped underneath. However, SEL does not consider the trapping of the fibres between the bars. SEL is an average value for a length of bar, independent of how much of the bar traps fibres. As an example of the importance of trapping, consider two refiners where the first refiner traps fibres on all of the length of the bar and the second traps fibres only along half the length of the bar. If the SEL is the same in both refiners, then same energy will be applied to only half the amount of fibres in the second refiner in comparison to the first and the treatment of the fibres in the second refiner will be twice as severe.

The key bar parameters affecting fibre trapping are bar velocity, distance between opposite bars and bar edge wear or rounding *(5-7)* as well as the bar surface structure and possibly the fillings' design. The shape of the leading bar edge is an important factor as this initially traps the fibres, forcing them to be draped across the moving edge. Both laboratory studies and mill practice have also indicated that new and sharp refiner bars shorten fibres to a greater extent *(8, 9)*. It is known that worn bar edges produce less efficient refining action *(7, 10)* while more energy is being consumed *e.g.* to reach a given paper tensile strength level. Meltzer showed that new fillings required a run-in period of 250 h before pulp drainage development was stabilised *(8)*. A more recent study by Filpus *(11)* reported that softwood refining with sharp bar edges resulted in more damaged fibres (torn and much fibrillated fibres) and that refining with worn and rounded bar edges resulted in significantly more intact fibres and less much fibrillated fibres, irrespective of the SEC or SEL-level. Another study comparing conical and plate fillings of a laboratory refiner reported that the leading bar edge of the conical fillings were rounder (0.172 vs. 0.037 mm). For conical fillings, the bar clearance increased with refining consistency while again the reverse was observed with disc fillings, which again produced more fibre shortening *(12)*. These observations would imply different fibre trapping in a disc and conical refiner, which might be due to the differences in geometry affecting the coriolis and centrifugal forces acting on the suspended fibres.

The main fibre parameters affecting trapping by bars are fibre length and width and pulp consistency *(13)*. Long fibres have a higher probability of being trapped than shorter fibres. As the refiner bars become worn their fibre trapping action varies due to changes in bar edge geometry since this affects the distribution of both fibres and forces in the refining gap. Unfortunately, direct observation of trapping at normal refining consistencies of 3-5 % is very difficult.

Previously we have developed a method *(14)* to indirectly measure relative changes in fibre trapping by measuring power consumption as a function of gap between rotor and stator bars. The two factors that characterise the refiner action in trapping and treating fibres are the fraction of the bar that traps fibres, which we defined as *f*, and the number of fibres trapped under the bar edge at each point where a fibre mat is trapped, which we defined as *i*. A schematic diagram of the concept is given in Figure 1. This shows a segment of rotor and of stator bar, each of length, *x*. Fibres have been trapped at five points along the bar and at each point, where fibres have been trapped, three fibres have been trapped, for a total of fifteen fibres. From this diagram, we have $f = 5d_w / x$ and $i = 3$, where d_w is the fibre width.

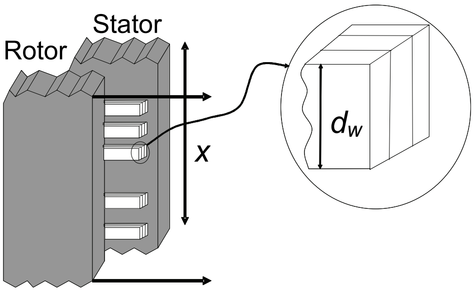

Figure 1 A schematic diagram showing three layers of fibres trapped at five positions along a bar of length, x.

The method *(14)* for estimating relative changes in fibre trapping was to measure refiner loadability for a given rotational speed and consistency. This is performed by measuring the refiner power consumed as a function of gap between the plates. To estimate the relative change in fibre trapping, the no-load power was fitted with a linear function while the net refining power was fitted with a negative exponential function. $P_{net} = c\exp(-g / g_t)$ The initial loading point, g_o, for each curve was then defined as the gap where the fitted net refiner power was 1% of the no-load power. For a given pulp it was then assumed that the number of fibre layers trapped at each point, i, was proportional to g_o. Thus for measurements on the same pulp, but at different operating condition, denoted 1 and 2, by definition

$$\frac{i_1}{i_2} = \frac{g_o^1}{g_o^2} \qquad 1$$

We were then able to show that provided it was assumed that the work of refining was consumed in working the fibres into a mat between the bar surfaces, then the ratio of the fraction of the bar surface trapping fibres for the two operation conditions was

$$\frac{f_1}{f_2} = \frac{c_1}{c_2}\frac{n_2}{n_1}\frac{g_o^2}{g_o^1} \qquad 2$$

Where n is the rotational speed. The full derivation is given in *(14)*.

In this paper we apply this method to examine how the state of the bar edge affects the fibre trapping process. This extends the work of our previous paper *(14)*, which looked only at the effect of consistency and refiner rotational speed.

Experimental method

A ProLab™ laboratory refining station supplied by Metso Paper was used in the experiments. The technical specifications of the refiner are given in *(14)*. The automated refiner handles softwood slurries of 2 to 7 % consistency at a typical batch size of 50 L. The refiner was operated with the rotor revolving in the non-pumping direction. The rotor position is measured by an inductive linear position sensor from the rotor axial movement. The position where the fillings come into contact was determined, while running the refiner dry at 1500 rpm, by a specific vibration level of the fillings as their zero point. A limitation of this zeroing procedure was that the contact position varied from measurement to measurement, with a range of ±0.03 mm around the average. A single such zeroing procedure was performed prior to each consistency series (1–6 %). A separate batch of pulp was prepared for each trial that were performed at pulp consistencies of 1, 2, 3, 4, 5 and 6 weight-percent. At each pulp consistency a refiner loading sequence for the gap of (2 mm - minimum - 2 mm) was consecutively performed at outer peripheral speeds of 4, 10, 15, 20 and 27 m/s (corresponding to 600, 1500, 2250 3000 and 4000 rpm, respectively) in between these refiner speed was increased in steps of 100 rpm per 15 s. Conventional refining trials were also carried out.

The softwood ECF-bleached dry lap kraft pulp used in the experiments was produced by a pulp mill in south-eastern Finland. The reinforcement pulp had a length-weighted fibre length of 2.44 mm and an average fibre coarseness of 0.183 mg/m.

Fillings

The A conical fillings used here had been previously run for several hundred hours in the refiner in the non-pumping direction. Their type is "LM" with a cutting length of 52.0 m/rev. The NewLM were prepared by running a used set of A fillings in the pumping direction (with applied power) with a suspension of quartz sand to sharpen the bar edges. The WornLM-fillings were then prepared from the NewLM fillings but with the edges manually worn down by abrasive paper. Micrographs of the fillings are shown in Figure 2 for the A and WornLM fillings. Unfortunately a similar shot of the NewLM fillings was not obtained before the edges were worn with abrasive paper.

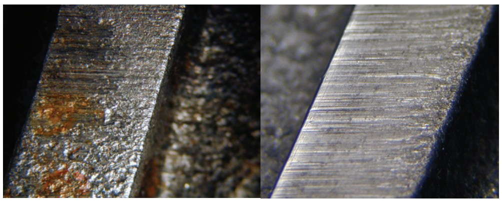

Figure 2. Typical wear on a bar of the standard A- (left) and WornLM-fillings (right). The width of the bar is 5 mm and the leading edge is to the right.

No significant differences at this scale can be seen between the bar edges of the A and the WornLM fillings. However it is notable that the surface of the two fillings looks significantly different. The A fillings are pitted while the WornLM fillings show a smoother surface with some scratches caused by the quartz sand and the abrasive paper.

The bar edge radii of the refiner fillings with three different degree of wear (NewLM, WornLM and A-fillings) were measured by analysis of digital images taken in an optical stereo microscope. For this purpose, 3D-negatives of the bar and groove geometry were produced using a high-resolution rubber (RepliSet-T1, a fast curing two-part silicon rubber compound, delivered by Struers Ltd.). The liquid rubber compound was applied to the sample area and was attached to a paper surface for curing. The solid negative was removed from the sampled fillings' surface, Figure 3.

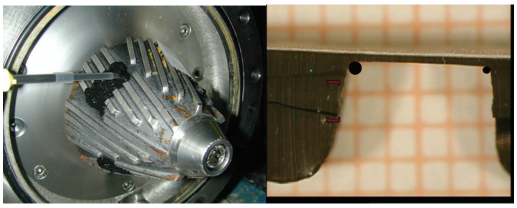

Figure 3. Application of rubber compound for creation of bar negative (left) and digital image with circles drawn onto bar edges on bar negative slice (right).

The rubber negatives were prepared for digital imaging by slicing perpendicularly across the bar direction. The bar edge radii were determined using the ImageJ software *(15)* by fitting a circle, scaled according to the 1x1 mm squares in the background, in the bar edge corner of the digital images, Figure 3. A minimum of four measurements were performed for each bar edge corner.

Results

The data for the radius of curvature are shown for the leading and leaving bar edges in Figures 4-5, respectively. Irrespective of the fillings, the leading rotor bar edges had a greater edge radius and were hence more worn than the leading stator bar edges, Figure 4 and Figure 5. Similar findings have been reported by a numerous authors *(1, 5-7, 16, 17)*. This would imply a higher degree of wear, probably due to fibre movement on the rotor bars. It could be thought that the rotor bar edges both distributes and traps the fibres whereas the stator bar edges to a greater extent act as collectors or anvils keeping the fibres in place. The moving rotor bars are thus subject to greater wear. The leaving stator bar edges of the A-fillings could not be determined reliable due to their deformed shape, Figure 5, which had been "stretched out" most probably upon clashing of the fillings.

The data for the leading bar edges in Figure 4 show that remarkably little difference. The average values for all three bar edges are within the limits of each other within the errors of the measurements. The leaving edge radius data shown in Figure 5 show that the NewLM and WornLM bars have higher bar edge radii than the A fillings, which is surprising. It should be remembered that the NewLM fillings were trimmed by running quartz sand and water through the refiner while it was operating in the pumping direction. The non-pumping direction was used in the refining trials. Switching directions means that a leading edge becomes a leaving edge and vice-versa. The quartz sand treatment was intended to trim the fillings for full parallelism, *i.e.* optimum bar contact area, of the rotor and stator bars. It seems clear that the trimming with sand has had the reverse effect for the leaving bar edge. However, given that the leading bar edge traps the fibres, not the leaving bar edge, it seems that the main difference between the A fillings and the WornLM fillings is that WornLM bars have a smoother, more regular surface. This point will be discussed further in light of the fibre trapping results which are presented next.

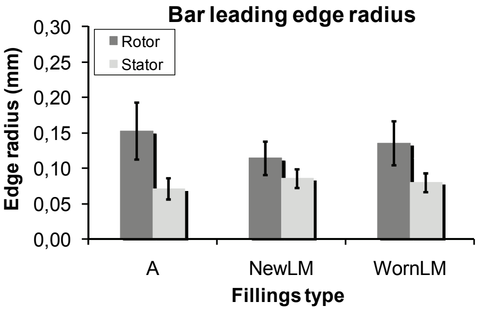

Figure 4. Edge radii of leading bar (non-pumping direction).

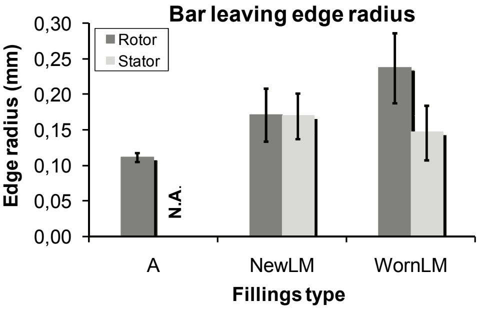

Figure 5. Bar edge radii of leaving edge.

In Figures 6-8 the initial loading points, g_0, are shown for the three sets of refiner fillings. For a given pulp, the initial loading point is proportional to the number of layers of fibres trapped under the bar at each point. Each figure shows the full set of data at each combination of refining speed and consistency. Some of these measurements have been shown in our previous publications *(13, 14)*.

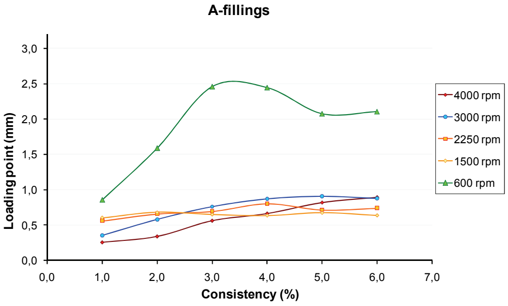

Figure 6 Loading point, g_0, as function of ECF$_2$-pulp consistency at various rpm's for the A fillings.

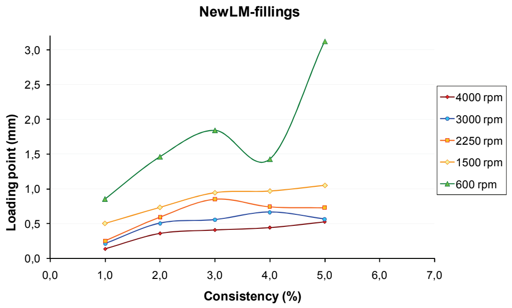

Figure 7. Loading point, g_0, as function of ECF$_2$-pulp consistency at various rpm's for the NewLM fillings.

All figures show that the 600 rpm data are very different from all the other data. The values of g_0 are much higher than at other speeds and the data generally display a maximum in the middle consistency range. As noted previously *(13, 14)*, the net refining power at all the speeds tested, except at 600 rpm, were well fitted with a negative exponential function. Net refining power versus gap at 600 rpm typically doesn't increase smoothly and was not well fitted by any of the functions that were sampled to fit the data.

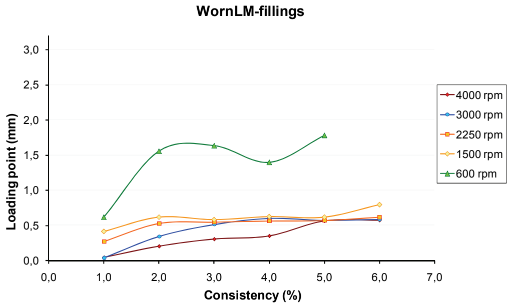

Figure 8. Loading point, g_0, as function of ECF$_2$-pulp consistency at various rpm's for the worn LM fillings.

We previously suggested that the unusual behaviour of the refiner at 600 rpm is due to the pulp being imperfectly fluidised and thus forming large clumps in the refiner. It is worth noting that g_0 for the 600 rpm data is closest to the data obtained at the other rotational speeds for the 1% consistency data, where the pulp would be easiest to fluidize. It is worth also noting that 600 rpm in this laboratory refiner produces peripheral speeds that are well below any commercial refiner. For all of these reasons the 600 rpm data was not further analysed.

Figures 6-8 also show that the general trends in g_0 are similar. For a given rotational speed, g_0 is approximately independent of consistency in the range 3-6%, while dropping off sharply at consistencies below this.

The values of g_0 shown in Figures 6-8 were used to convert the gap measurements in the loadability trials to "strain" values by setting $\varepsilon = 0$ when $g = g_0$. These are not strain values in the standard sense of mechanical testing, since the pulp is continually circulating through and around the refiner and the material in the gap keeps changing. Data are shown here only for 1500 and 4000 rpm. Figure 9 and Figure 10 give the data for the A-fillings. Figure 11 and Figure 12 give the data for the NewLM fillings, while Figure 13 and Figure 14 give the data for the WornLM fillings. The 2250 and 3000 rpm data give similar trends and so have been omitted for reasons of space. For these figures, the net power data has been corrected for rotational speed, *n*. Given that each set of fillings has the same cutting edge length; this means that the y-axis values are proportional to SEL, with the same constant of proportionality for all three figures. For the same value of g_0 the power required to run refiner at given strain will be directly proportional to the fraction of the bar edge trapping fibres, *f*. When the data at the same consistency are compared it can be seen that in general the A fillings require the most power at a given level of strain, while the Worn LM fillings require the least.

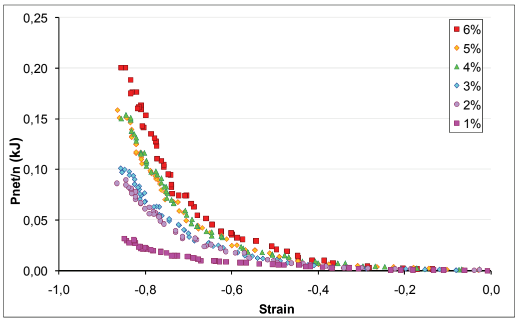

Figure 9. 1500 rpm, P_{Net}/n for the A fillings

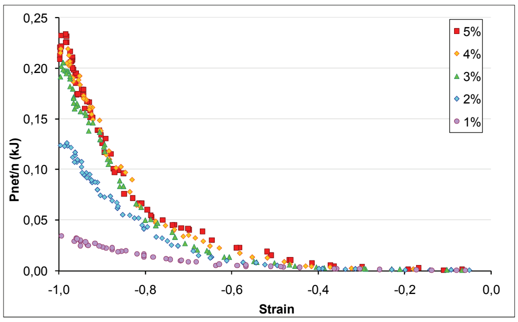

Figure 11. 1500 rpm, P_{Net}/n for the New LM fillings.

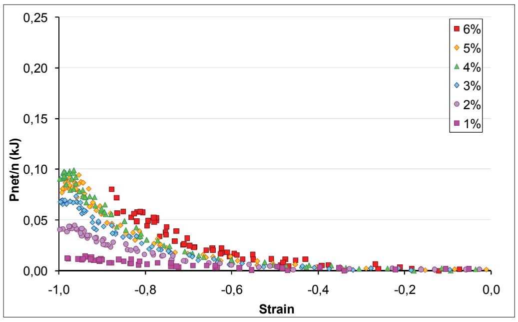

Figure 13. 1500 rpm, P_{Net}/n for the Worn-LM fillings.

Figure 15-Figure 17 show the calculated values of *f* for the set of consistencies and speeds for the three fillings. The method of analysis only allows values of *f* to be calculated as a ratio of results for two sets of refining conditions. This step was required to cancel out constants which were unknown. For this paper it was decided to set 1500 rpm and 6% consistency as the reference condition and to assume that *f*=1 at this reference condition. All other data have been calculated from this reference.

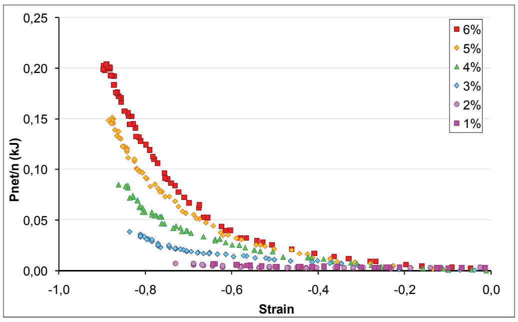

Figure 10. 4000 rpm, P_{Net}/n for the A fillings

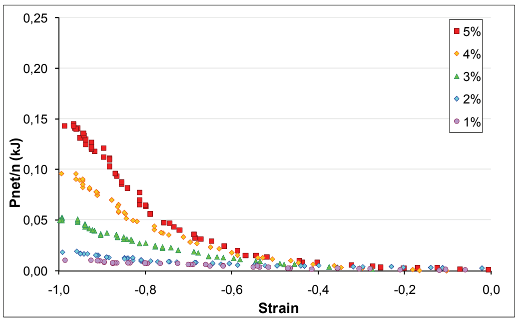

Figure 12. 4000 rpm, P_{Net}/n for the New LM fillings.

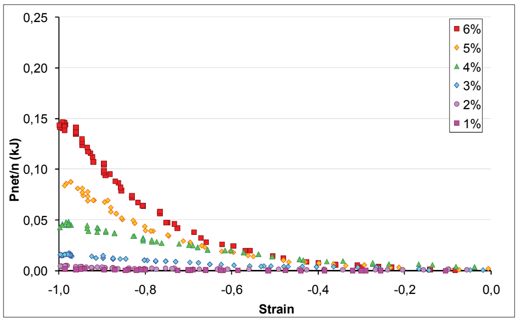

Figure 14. 4000 rpm, P_{Net}/n for the Worn-LM fillings.

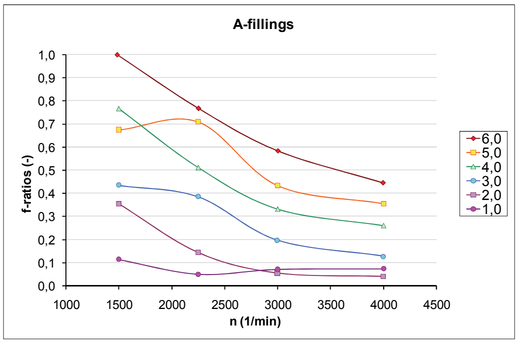

Figure 15 Relative change in f with consistency and refiner speed for the A fillings. It is assumed that f=1 at 1500 rpm and 6% consistency for the A-fillings.

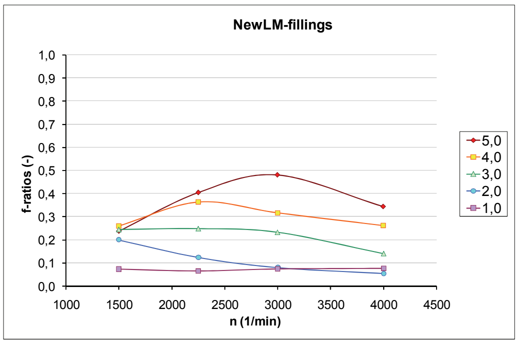

Figure 16 Relative change in f with consistency and refiner speed for the NewLM fillings. It is assumed that f=1 at 1500 rpm and 6% consistency for the A-fillings.

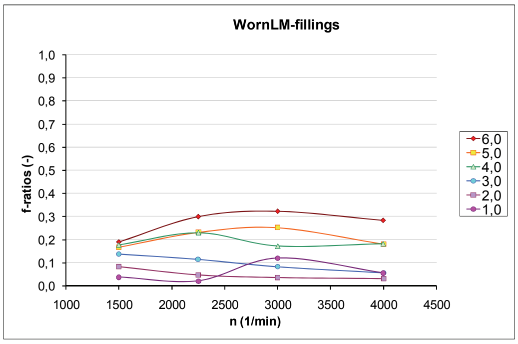

Figure 17 Relative change in f with consistency and refiner speed for the WornLM fillings. It is assumed that f=1 at 1500 rpm and 6% consistency for the A-fillings.

Figure 15 for the A fillings show that *f* falls with increase in speed or reduction in consistency. The data for the NewLM and WornLM fillings are given in Figure 16 and Figure 17, respectively. The data for the the NewLM and WornLM fillings show low relative values of *f* in comparison to the A fillings shown in Figure 15. The NewLM and the WornLM data also show somewhat different behaviour with speed than the A fillings, in that the data for 3-6% consistency shows a local maxima in fibre trapping with speed. The data at 2 and 1% consistency behave similarly to the A fillings shown in Figure 15 in that *f* drops with increasing speed. All three figures show similar trends with consistency, that a decrease in consistency produces a reduction in *f*.

It is also important to show that these changes in fibre trapping lead to measurable differences in refining outcome. Figure 18 shows the development of fibre length for several runs at different SELs for each of the three sets of fillings. It can be seen that the data is quite consistent with the data for *f* shown above. For similar values of SEL the WornLM and NewLM fillings provide a much harsher treatment than the A fillings, resulting in a much more rapid shortening of fibre length.

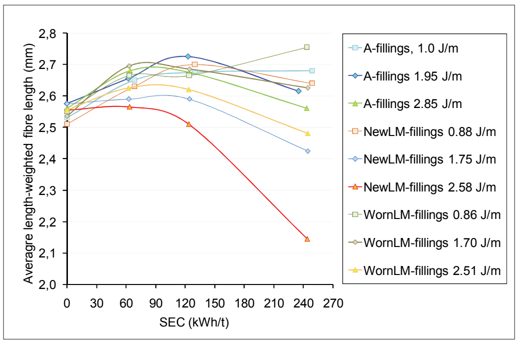

Figure 18 Fibre length development with specific refining energy for the A, NewLM and WornLM fillings for refining trials conducted at 3000 rpm. The data was taken from (11).

We are then faced with speculating as to why treatments that have produced the NewLM and the WornLM fillings have had such a negative effect on the fibre trapping, which has correspondingly increased the harshness of the refining process. Certainly there is no evidence in the bar-edge radii data shown in Figure 4 and Figure 5 of any large differences in the bar edge radii that could explain such differences. One possibility is that the measurement method has failed to capture all of the parameters of the bar edge involved in trapping *(18)* or that fine serrations seen on the surfaces of the WornLM bars has interfered with the measurement *(18)*.

It should be noted that the method we have used may exaggerate differences between fillings since the calculation assumes all energy in refining will be consumed in working fibres into gap between rotor and stator bar surfaces. This assumption ignores the work of sliding the rotor bar over the compressed mat of fibres. It is possible that there may be some differences between the Worn, New LM and the A fillings from this sliding work. While a micrograph of the NewLM surface was not available, Figure 2 for the WornLM surface showed that a much more regular surface than the pitted surface of the A fillings shown in Figure 2, which may have produced some difference in sliding work.

However, despite the preceding discussion, it is clear that the NewLM and WornLM fillings have been less effective than the A-fillings at trapping fibres. By process of elimination we are left with the tentative conclusion that the bar surface might also be playing a role in the trapping the fibres. It may be possible that the small scale pocked roughness seen in the picture of the A-fillings has been more of more use in trapping fibres than the smoother scored surface of the WornLM fillings. This is an interesting hypothesis, given that it has generally been assumed that it is the bar edge that has been the critical factor and is certainly a hypothesis that should be tested in future work.

Conclusions

A method for characterising fibre trapping in refining was used to examine differences in fibre trapping between three sets of fillings used in a laboratory refiner. The two sets of fillings with artificially prepared bar edges showed greatly reduced fibre trapping in comparison to fillings with fillings that had been worn in during standard refining trials. Fibre length data showed that the reduction in fibre trapping increased the severity of the refining process.

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