How Is Frayed Fiber Generated during Refining Process? (Identification of Frayed Fiber under High Resolution Microscope)

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ABSTRACT

The objective of this study is to characterize frayed fiber[1] under high resolution microscope to unveil fiber fraying. Based on observation with high resolution microscope, the classification of frayed fibers has been done to contribute to clarifying fiber fraying mechanism. One rectification on previous recognition of frayed fiber has been made to indicate that the dominating cases for fiber fraying are many fibers fraying in one point instead of single fiber fraying at fiber cut site as previously reported[1]. Thus the rectification/removal of fallacious knowledge of frayed fiber favors to clarify this issue. It is further indicated that the unveiling or clarification of fiber fraying mechanism is mainly based on the integration between classification of frayed fiber and traditionally proven effects of refining on various fiber changes from LC to HC refining process. Thus, a latest and newly-built theory responsible for fiber fraying during refining process has been proposed in this paper. With convincing reasoning and speculation, this newly established theory proposed in this paper could go through various visible phenomena and effects of frayed fibers as published earlier[1]. This theory proposes that frayed fibers are generated based on the integration of "splitting" and "locally high consistency" mechanisms. In other words, the intensive external fibrillation responsible for "splitting" and "locally high consistency" theory is one of the most important effects of refining on frayed fiber generation. Therefore, the origin of fiber fraying could be the intensive external fibrillation(LC refining at high energy) integrated together with certain fiber type (SW), the methodology of fiber processing(BSKP), refiner type(Escher Wyss) and friction between fibers and equipment. This theory further indicates that any intensive external fibrillation equivalents generated in any conditions other than LC refining at high energy also permit fiber fraying generation.

INTRODUCTION

Review of frayed fiber

Figure 1 is a picture of frayed fiber under Scanning Electron Microscopy (SEM). PFI mill refined BSKP pulps do not show any newly found refining effects on fiber characteristics. On the contrary, a large population of a new type of fibers with new specifications were reported to be generated with the same BSKP pulps during LC refining at high energy with Escher Wyss refiner. Fibers with these new characteristics were termed frayed fibers by Dr. Mousa[1].

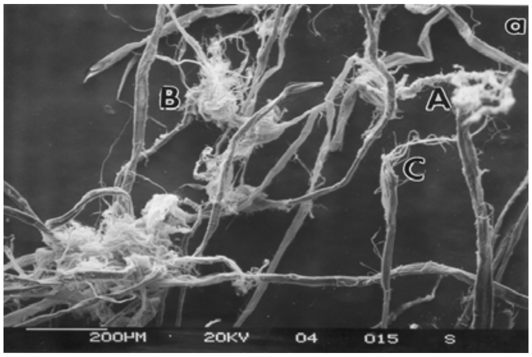

FIGURE 1. Frayed fiber cut by Escher Wyss refiner under Scanning Electron Microscopy (SEM)[1].

The frayed point looks like a jellyfish in water and thus encounters difficulties in its dimension quantification. These so called frayed fibers are proven not to disperse by agitation as it is the case of fiber flocs and thus cannot be categorized as fiber flocs. The white point (frayed point) is an intensely frayed site indeed. And it was further reported that a typical frayed fiber was either single or two fibers intensely frayed in one point along the fiber length. Anyhow, the frayed point irreversibly alters the appearance of these fibers from the rest of the pulp and thus provides them a new identity. These fibers could exist in some of the pulps which had refining experience. But it is noted that fiber fraying is not a typical consequence of refining and it could be present in LC refined pulps or mechanical pulps. Thus it was concluded that the refining might generate a new type of fibers for certain pulps(most probably softwood) at different refining conditions. The frayed fiber cut site is an intensely frayed site after complete fiber rupture. Fiber cut during refining, resulting in fiber shortening is a split at the frayed point along the fiber length. From the above figure, fiber fraying together with external fibrillation could be origin of fines generation.

Because of the contribution of higher fiber bonding due to this intensely entangled/frayed point, frayed fiber could indicate high potential in reinforcement pulps and packaging grade which have high strength requirements. It was further indicated that frayed fibers could show difficulties in going through screening apertures at screening stage. Therefore, Dr. Mousa further indicated that recognition of these fibers could bring considerable savings in the form of raw materials and energy.

MATERIALS AND METHODS

Materials

A Canadian CTMP donated by a local pulp mill; three bleached softwood kraft pulps (BSKP) refined with PFI refiner at fixed speed of 12,000 RPM at 1000, 3000 and 5000 revolutions, respectively; three BSKP pulps refined with PFI at fixed speed of 12,000 RPM in 3, 5 and 10 minutes, respectively; The Escher Wyss refiner was used to refine a BSKP pulp at SEL of 3 Ws/m and SE of 100 kWh/t and another BSKP pulp at SEL of 1 Ws/m and SE of 300 kWh/t , respectively. It is noted that these pulps used had more or less refining history.

Methods

High resolution microscope OLYMPUS BX 50 was used at 80X, 200X, 400X magnification, respectively. Each of above refined pulps was disintegrated to make it uniform, then a small amount of sample was taken from the pulp and diluted in the table-water bottle. After that, an observation was done to identify whether there were some white points as individuals (possible candidates for frayed fibers) in the fiber solution. These white points were then taken out from the fiber solution and placed on the slide ready for microscope observation.

Under high resolution microscope, observations at fiber scale were done to characterize detailed structure of both frayed fiber and normal fiber and thus a comparison could be made between them concerning fiber cutting and peeling, fines generation, the difference between fiber flocs and frayed point, splitting at the fiber end or cut site or along the fiber length, the morphologic structure of frayed point. Furthermore, the frayed point generation mechanism was trying to be identified.

The major scope or difficulty of this research is to identify a typical frayed fiber made of one or two fibers intensely frayed in one point as compared to a frayed fiber comprised of many fibers intensely frayed in one point in pulp suspension to unveil the issue of frayed fiber and clarify the case with frayed point made of many fibers. The main reason is that the detailed structure of frayed point made of single or two fibers is clearly visible under high resolution microscope whereas the case of frayed point comprised of many fibers is not visible for both a naked eye or even high resolution microscope. Furthermore, only a few cases with frayed point of one or two fibers exist in pulp suspension mixed with the dominating cases with many fibers fraying at one point. Then the most important refining effects on fiber fraying were thus trying to be proposed.

RESULTS AND DISCUSSION

The results showed that the pulp refined with Escher Wyss at SEL of 3 Ws/m and SE of 100 kWh/t contained a large population of a new type of fibers with new specifications which are referred as frayed fibers. With the exception of the above case, the other pulps examined didn't contain any visible physical effects other than previously reported in the literature for both a naked eye and high resolution microscope.

THE APPEARANCE OF FRAYED FIBER FOR BOTH A NAKED EYE AND MICROSCOPE

FIGURE 2. Frayed fiber in suspension

Frayed fiber is irregular and appears as a jellyfish in water and thus cannot be quantified[1].

COMPARISON OF FIBER CUT SITE BETWEEN NORMAL FIBER AND FRAYED FIBER

<u>Intact fiber end</u>

FIGURE 3. Intact fiber end

Incomplete frayed fiber cut

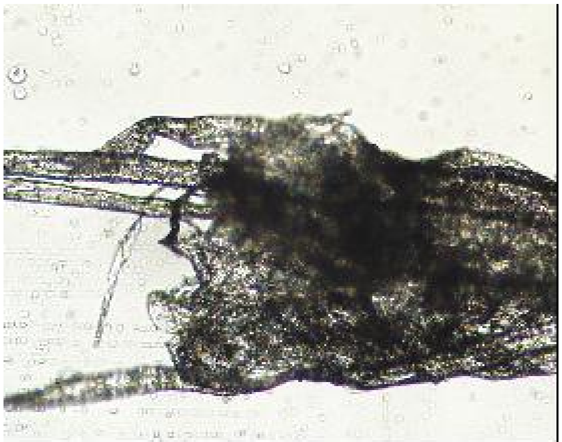

FIGURE 4. Incomplete frayed fiber cut

Complete fiber cut of frayed fiber

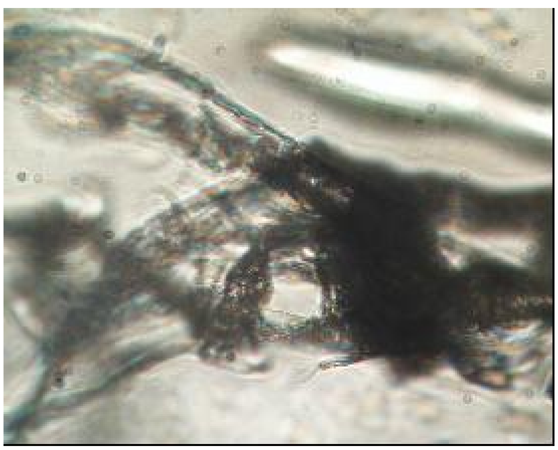

FIGURE 5-a. Complete frayed fiber cut

FIGURE 5-b. Complete frayed fiber cut

From *Figure 3, 4 and 5*, intact fiber end is a regular fiber end and doesn't show any large degree of splitting as it is the case with either incomplete or complete frayed fiber cut. In addition, the splitting degree of normal fiber cut is not as pronounced as frayed fiber cut, which could be an indication that splitting could be the prerequisite contributing to frayed fiber generation. It is noted that since at fiber cut site, different fiber layers are exposed to shear forces from both water and refiner bars, fiber cut site is a usually a vulnerable area which is easier to suffer from these forces and thus generate a much higher degree of fiber splitting than along the fiber length as indicated in figures above.

Fiber cut could be present in either incomplete fiber rupture or complete fiber rupture as illustrated in above figures. The cut site is an intensely frayed site after complete fiber rupture. It is further indicated that fiber cut during refining, resulting in fiber shortening is a split at the frayed point along the fiber length. As it is generally thought, the fiber cut in refining is not a clean and sharp knife cut.

Fines generation

FIGURE 6-a., FIGURE 6-b. Fines generation

Figure 6a and Figure 6b indicate that fines are either fragments or splits isolated or fragmentated from along the fiber length or at the fiber cut site. Fines were always identified during observations of frayed fibers under high resolution microscope. This observation could be an indication that fiber fraying together with traditionally proven external fibrillation is the origin of fines generation. So, fibers are not generated by fiber shortening or fibrillation per SE as it is generally thought.

COMPARISON OF MORPHOLOGIC STRUCTURE AND SPLITTING DEGREE BETWEEN FIBER FLOCS AND FRAYED FIBERS

Morphologic structure of fiber flocs (white point for a naked eye in fiber solution from pulp refined at SEL and SE of 3Ws/m and 100kWh/t)

FIGURE 7. Fiber flocs in pulp suspension without frayed fiber

Fibers fraying in one point

FIGURE 8. Fibers fraying in one point

Figure 7 and Figure 8 compare the morphologic structure and splitting degree between fiber flocs and frayed fibers. Results showed that fiber folcs are pieces of pulps for a naked eye. Under high resolution microscope, in the case of fiber flocs, fibers overlap or weakly entangle/bond together and thus disperse by high energy agitation whereas in the case of frayed fibers, more or less fibers are intensely frayed in one point so they do not disperse by agitation as it is the case with fiber focs. Therefore, they do not fit in the category of fiber flocs. In addition, these figures also suggest that frayed fiber permits splitting to a much higher extent than that of fiber flocs, resulting in much more pronounced fiber entanglements which could account for their totally opposite behavior during high energy dispersion.

BIGGER FRAYED POINT MADE OF SMALLER FRAYED POINT

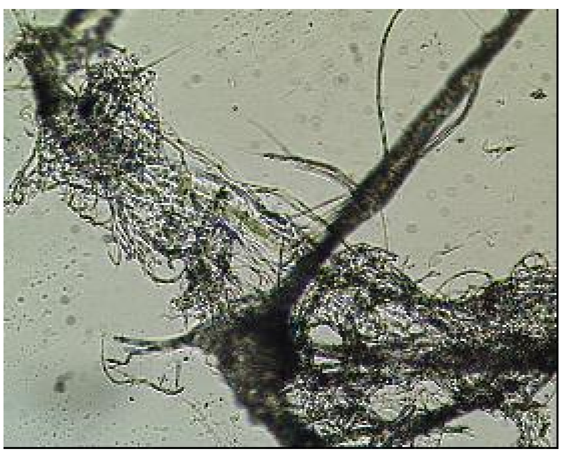

FIGURE 9. Bigger frayed point made of smaller frayed point

Figure 9 further indicates that frayed point as a whole for a naked eye in pulp suspension could occur with the case that this frayed point is comprised of at least one smaller frayed point as illustrated above. Thus they interact with each other and function as one frayed point in pulp suspension indeed.

CLASSIFICATION OF FRAYED FIBER

Frayed point comprised of single fiber

FIGURE 10. Frayed point comprised of single fiber is a frayed fiber cut site indeed.

Figures 4, 5a, 5b, 6b and 10 show frayed point comprised of single fiber is a frayed fiber cut site indeed. Since such single frayed fiber only exists as a few cases in frayed pulp suspension, this is the difficulty we encountered to identify the single fiber fraying in one point mixed with the dominating cases with many fibers fraying at one point. However, the detailed structure of frayed point made of single or two fibers is clearly visible under high resolution microscope whereas the case of frayed point comprised of many fibers is not visible for either a naked eye or even high resolution microscope. Therefore, identification of such typical frayed point made of single fiber contributes to clarifying the case with many fibers fraying at one point and thus unveiling the frayed fiber issue.

Frayed point comprised of two fibers

FIGURE 11. Frayed point comprised of tow fibers

Frayed point comprised of many fibers

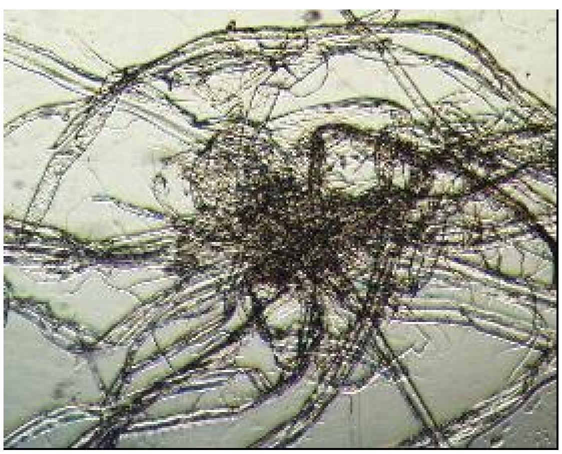

FIGURE 12. Frayed point comprised of many fibers

Figure 12 indicates that many fibers fraying in one point is not visible for both a naked eye and even high resolution microscope. However, with analysis and clarification of the generation mechanism of frayed point comprised of single or two fibers, the generation mechanism for the dominating cases with many fibers fraying in one point in pulp suspension could be reasonably speculated upon.

MECHANISM FOR FRAYED FIBER GENERATION

a

b

FIGURE 13. Mechanism for frayed fiber generation

In the case of Escher Wyss refined BSKPH pulps with LC at SEL and SE of 3Ws/m and 240kWh/t, sufficiently high forces act on fibers which are relatively fixed and thus cannot escape these forces(shear forces are predominant on compression forces) during LC refining which is based on bar to fibers interaction. Thus the external fibrillation occurs together with more or less fiber peeling, cutting and fines generation. In this case, since LC refining was performed at high SEL and SE, external fibrillation, fiber cutting and peeling were more pronounced, thus resulting in large degree of splitting, fibrillated surfaces in any point along the fiber length or fiber cut site which offer the possibility and intensity for fiber entanglements along its fiber length or at the cut site. Thus it could explain the case of two/many fibers frayed in one point. On the other hand, the frayed fiber cut has been identified as an intense split at the frayed point along its fiber length. This case might be responsible for the frayed site made of single fiber. Therefore, large degree of splitting, fibrillated surfaces and the intense splitting at the frayed fiber cut site during LC refining process at high energy are generated due to intensive external fibrillation and thus interact with each other to contribute to generating frayed points made of different amounts of fibers. Thus, these fiber splitting entanglements are intense enough to resist shear forces of water and refiner bars and thus do not disperse by agitation as it is the case with fiber flocs. Thus these entangled fibers were identified as a new type of fibers and termed "frayed fiber". It is noted that once one frayed point is generated, it is most probably under the intensive external fibrillation, so similar splitting effect could most probably acts on this entangled point and thus this frayed point becomes more "pronounced" until the splitting effect levels off.

Not only does Intensive external fibrillation generate sufficiently high splitting necessary for fiber fraying, but it also creates the "locally high consistency" to make fibers come close together to favor fiber entanglements. As is well-known to all, when refining energy which is the combined effect of SE and SEL is increased from low to high level, centrifugal effect of refiner is more pronounced, and thus fibers have a tendency to move towards the refiner border and become closer to create "locally high consistency" to get entangled with each other and thus favor the generation of frayed fibers.

All in all, the above "splitting" and "locally high consistency" theories integrated together as a whole generate frayed fibers. In other words, the intensive external fibrillation responsible for "splitting" and "locally high consistency" theory is one of the most important effects of refining on frayed fiber generation. Therefore, we could say the origin of fiber fraying is the intensive external fibrillation(LC refining at high energy) during refining process integrated together with favorable fiber type (SW), the methodology of fiber processing(BSKP), refiner type(Escher Wyss) and friction between fibers and equipment. This theory further indicates that any intensive external fibrillation equivalents generated in any conditions other than LC refining at high energy (LC favors "splitting" whereas high energy favors "locally high consistency") also permit fiber fraying generation. By the way, the generation of fiber flocs also can be explained with this theory as follows: during refining process, fibers could come close together to become "locally high consistency" to get entangled with each other due to above centrifugal effect. However, these entangled fibers disperse by agitation due to lack of large degree of splitting which favors intense fiber entanglements as compared to the case with fiber fraying. Thus these dispersed fibers as the contrary case with frayed fibers are traditionally termed "fiber flocs".

This theory could answer "frayed fiber is not a typical consequence of the refining process."[1] because not all refining processes can provide intensive external fibrillation to generate frayed fiber. On the contrary, this theory could explain why frayed fibers were only generated and previously found in pulps with more or less refining history[1]. This could be because among all the papermaking processes, due to the internal and inherent structure of refiner, only refining process could provide the possibility to generate sufficiently high external fibrillation which is responsible for large degree of splitting, fibrillated surfaces required for fiber fraying.

This mechanism may also clarify "the frayed site is a possible candidate for fiber cut in refining process"[1], because large degree of splitting, fibrillated surfaces permit to generate frayed fiber at any point along fiber length other than the cut site.

Based on the above "fiber splitting" mechanism, it could explain "it could be part of any pulp(most probably softwood pulp), which has refining experience in its production line"[1] because the similar splitting to more or less degree could be present during different refining process. On the other hand, frayed fiber is generated most probably in softwood pulp because SW pulp abundant in long fibers which favor fiber cut has much more potential to generate more splitting at the cut site and offer the large degree of fiber peeling, thus inducing large degree of splitting, fibrillated surfaces which favor frayed point generation.

In addition, this splitting mechanism could also explain "frayed fibers are not a typical consequence of refining process, and it could be present in either LC refined pulps or mechanical pulps"[1]. According to previous publications[2] when comparing the average performance of LC to HC refining on fiber fibrillation and fines generation, little difference is observed. However, LC refining at high energy permits to develop external fibrillation to a much higher extent than that of HC refining. In other words, fiber peeling and cutting contributing to splitting which favors frayed fiber generation are much more pronounced during high energy LC refining as it is the case of this experiment.

This theory goes through this point that fiber fraying favors softwood instead of hardwood or non-wood. Reasons are listed as follows: Firstly, SW has highest level of cellulose and hemicellulose and thus offers highest potential for fiber splitting which is favorable

to fiber fraying. Secondly, SW with longer fiber length than HW during refining favors more pronounced fiber cutting which is characterized by a split at the cut site. In addition, SW which is characterized by a thinner fiber cell wall than HW shows higher potential in large degree of splitting along the fiber length definitely than HW or non-wood due to easier separation of different fiber layers which contributes to favorable peeling along fiber length. Moreover, the strong kraft pulping for SW favors most pronounced lignin removal and thus contribute to SW fiber softening which makes different cell wall layers separation easier. Finally, since SW fibers are less coarse than HW due to thinner cell wall thickness, SW fibers have higher collapsibility due to fiber swelling. Thus the higher collapsibility for SW increases fiber flexibility which improves fiber bonding ability contributing to the entanglement of frayed fibers.

It is further indicated that this splitting mechanism could illustrate how the methodology of fiber processing affects frayed fiber generation. According to previous publication, under the same Escher Wyss refiner conditions, frayed fiber fraction for bleached softwood kraft pulp(BSKP) could be as high as 60% whereas that was 10% for US southern pine thermo-mechanical pulp(TMP) and frayed fibers were not found to be a pulp component in Canadian balsam/spruce TMP[1]. In addition, the Canadian chemical thermo-mechanical pulp (CTMP) used in this experiment didn't show any fiber fraying phenomenon. In other words, fiber fraying favors BSKP instead of TMP or CTMP pulping method. Reasons could be that TMP and CTMP pulping methods are mainly based on lignin-preserving(the pulping yield mainly in the range of 85~90%[3]) while BSKP pulping is mainly based upon lignin-removal(The pulping yield mainly in the range of 40~50%[3]). That is to say that the content of cellulose and hemicellulose for BSKP is much high than that for TMP or CTMP. Thus, the high content of cellulose and hemicellulose for BSKP offers the highest potential of large degree of splitting, fibrillated surfaces which favor fiber fraying during refining process. However, TMP or CTMP could not provide the above high splitting potential due to frequent disturbance of the presence of fragmented lignin during refining process and much lower amount of cellulose and hemicellulose as compared to the case of BSKP. In other words, the methodology of fiber processing is also a prerequisite for frayed fiber generation(the lignin-removal pulping method preferred, e.g. BSKP).

WHY CAN'T PFI GENERATE FRAYED FIBERS AS IT IS THE CASE OF ESCHER WYSS? HOW ABOUT THE COMPARISON BETWEEN LAB SCALE REFINERS AND INDUSTRIAL SCALE REFINERS?

The theory explains why PFI can't generate frayed fibers as it is the case with Escher Wyss. Thus, the comparison between lab scale refiners and industrial scale refiners could be deduced.

PFI mill is very different from commercial mill whereas Escher Wyss is somewhat similar to commercial scale refiners. It could be because the more potential internal fibrillation with PFI which is characterized by a partial delamination of fiber cell wall, thus resulting in less pronounced splitting, fibrillated fiber surfaces which do not favor frayed fiber generation. Another reason is the lack of bar to fibers interaction with PFI as compared to Escher Wyss, thus resulting in less pronounced fiber cutting which leads to less amount of splitting at fiber cut site. Therefore, less pronounced splitting, fibrillated fiber surfaces together with less amount of splitting at fiber cut site could be identified to reduce the possibility and intensity of fiber entanglement which favors fiber fraying.

The comparison between PFI (higher internal fibrillation) and Escher Wyss(higher external fibrillation) was enlightened from the comparison of HC and LC refining which are mainly based on internal fibrillation and external fibrillation, respectively. This idea is based on the comparison of water flow type between PFI and Escher Wyss. PFI is a disc refiner characterized by a regular fiber flow which permits fibers to move towards the disc border and become closer together to create "locally HC" fiber flow which could increase fibers to fibers interaction and compression forces between fibers which are both responsible for internal fibrillation. On the contrary, Escher Wyss is a conical refiner characterized by irregular/turbulent fiber flow which favors higher fiber mobility and more uniform fiber flow, thus resulting in "locally LC" fiber flow as compared to the case with PFI. Because of the structural differences between PFI and Escher Wyss, PFI mill refined fibers are relatively fixed during refining process and fibers lack of mobility in pulp suspension as compared to the case with Escher Wyss which could be characterized by higher fiber flow mobility in refining process. Thus, fibers refined with PFI mill have less opportunities to touch or interact with refiner bars, which results in less pronounced fiber cutting and fiber peeling which both do not favor large degree of fiber splitting, fibrillated surfaces which contribute to fiber fraying along the fiber length or at the cut site. In addition, due to lack of bar to fibers interaction with PFI mill, fibers to fibers interaction and compression forces which both together contribute to internal fibrillation must be more pronounced than with Escher Wyss.

Therefore, higher internal fibrillation could occur with PFI whereas Escher Wyss could be characterized by higher external fibrillation, or vice versa. In other words, the refining effects of PFI as compared with Escher Wyss on fiber characteristics are less pronounced than with Escher Wyss: less fiber cutting which contributes to less fiber shortening, longer fiber length and less average degree of splitting at fiber cut site; less fiber peeling resulting in less splitting, fibrillated fiber surfaces which do not favor fiber fraying; less fines generation; less curl and kinks removal.

This comparison between PFI(internal fibrillation) and Escher Wyss(external fibrillation) could explain how friction between fibers and equipment affects the amount of frayed fibers. For one thing, it could clarify why fiber fraying was more pronounced for Escher Wyss refined BSKP pulp when the specific energy(SE) or the refining intensity(SEL) increased further according to previous publication[1]. In this case, the external fibrillation increased with refining energy increase which is the combined effect of SEL and SE. Thus, the increased external fibrillation provided stronger bar-to-fibers interactions which generated more pronounced friction between fibers and refiner bars, resulting in a higher degree of splitting, fibrillated fiber surfaces that favor fiber fraying. And the fiber cutting was also more intensive simultaneously and thus offered more frayed sites in the fiber cut sites. On the contrary, this comparison could also clarify why the BSKP pulps refined with PFI at a fixed speed by anyway changing refining revolutions and refining time in this experiment didn't show any fiber fraying phenomenon. Because the PFI refiner is characterized by a higher level of internal fibrillation which could be mainly based on fibers-to-fibers interactions, i.e., mainly friction between fibers. Friction of this kind is characterized by a partial delamination of fiber cell wall and hence it is too limited to provide large degree of splitting, fibrillated surfaces required for fiber fraying when compare with the case of Escher Wyss refined pulps.

SUMMARY AND CONCLUSION

The rectification should be done at this point "frayed fibers are either single fiber or two fibers intensely frayed in one point." First of all, the above case could exist definitely in frayed fiber suspension. However, single or two fibers intensely fraying in one point belongs to a few cases mixed with the dominating cases with many fibers fraying at one point. This is the difficulty for this research to identify the single frayed fiber under high resolution microscope. Therefore, it is proposed that single frayed fiber should definitely go through screening holes or slots and cleaning systems during production process. Instead, possible rejection problems of frayed fiber in screening and cleaning systems could only happen in the dominating cases with many fibers fraying in one point as it is observed under high resolution microscope.

Frayed points could overlap together to form a bigger frayed point as a whole and interact with each other and function as one frayed point in pulp suspension indeed. Under high resolution microscope, frayed points could be at least classified into three categories: single fiber fraying, two fibers fraying, many fibers fraying intensely in one point, respectively. And the fiber fraying mechanism thus could be deduced based on analyzing the above classification of frayed fibers.

Sufficiently high external fibrillation(low consistency refining at high energy) has been found to be the most important effect of refining on frayed fiber generation under the most favorable prerequisite conditions that indicate highest potential of fiber splitting during the following refining process. These favorable conditions for fiber fraying could be softwood fiber type(high cellulose content), kraft pulping method(BSKP, lignin-removal), Escher Wyss refiner type(high external fibrillation), and strong friction between fibers and equipment(favorable for fiber peeling). On the contrary, the unfavorable or adverse conditions for fiber fraying could be listed as follows: intensive or high internal fibrillation (mainly fibers to fibers interactions), hardwood or non-wood fiber type(low cellulose content), lignin-preserving pulping methods(GW, RMP, TMP, CTMP etc.), PFI refiner type(high internal fibrillation), high refining consistency (around 20~30%[3], high internal fibrillation during refining process), weak friction between fibers and equipment(low splitting degree), SE and SEL(the lower refining energy, the weaker refining effect).

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