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# Towards optimal defibration: Energy reduction by fatiguing pre-treatment

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**KEYWORDS:** Defibration, Fatigue, Mechanical Pulp, Energy, Efficiency

**SUMMARY:** A motive for fatiguing wood prior to defibration would be to reduce the energy consumption needed in mechanical pulping processes. Therefore, the effects of fatiguing pre-treatment were here studied on wood samples, on defibration and also on produced paper. The results indicate that pre-fatiguing changes the mechanic response of wood to be more favorable for harsh defibration which in turn is positive for the process efficiency.

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All types of mechanical pulping equipment produce large deformations of fiber walls in wood. The repeated cyclic loading applied to wood material during the production process cumulates as fatigue.

Papermaking fibers should preferably be long, slender and have a high bonding ability. For this reason energy effective high temperature defibration, where lignin is thermally softened, is not always viable since it produces fibers which do not bond particularly well. Thus, fatigue pre-treatment, which has been reported to enable the use of harsh mechanical defibration and thereby provide energy reducing opportunities (Salmi et al. 2012b), could be beneficial. The concept leads to loosening of the wood matrix and therefore instead of getting cut during harsh defibration, the fatigued wood fibers are pliable and prone to liberate.

Fatigue in mechanical pulping is generally known to produce internal fibrillation in the fiber material, which is needed to produce slender fibers with high bonding ability (Kärenlampi et al. 2003; Maloney, Paulapuro 1999). Fatigue work is, however, connected to constraints that make the pulping task a compromise between desired work, efficiency and intensity of the mechanical work. The intensity term is in this discussion not strictly defined but relates to the stress-strain-level applied to the fiber

material and is comparable to ‘refining intensity’ and ‘fiber peeling harshness’ in thermomechanical pulping and grinding discussions respectively (Miles, May 1990; Lucander, Björkqvist 2005). Since the wood material is viscoelastic, low intensity defibration actions cause small wood matrix deformations and minor cell wall surface damages. Small deformations i.e. low strain produces insignificant amounts of desired fatigue and thus low energy efficiency in the mechanical breakdown of wood structure and wood fibers. This material behavior leads to the generally approved hypothesis that the higher the intensity of the process deformations is the higher is also the efficiency of the desired work (Salmén et al. 1985). High intensity defibration is thus favorable but too much fiber damage or fiber cutting should be avoided. The main principle is shown graphically in *Fig 1*.

Here efficiency is defined as desired work divided by total mechanical work. Desired work is again defined to include only the pure energy used for production of new internal and external surfaces i.e. opening and loosening of wood structure but not to include the corresponding heat dissipation which inevitably occurs in deformations of materials with internal friction i.e. viscosity (Salmén, Fellers 1982).

It is however possible to affect the intensity limit for undesired damage. Wood moisture content and temperature are both in active industrial use to push the limit to higher values. Chemical pre-treatment of wood raw material is also growing in use for the same purpose but utilization of fatigue is not so obvious even if it is to some extent present in the main industrial mechanical pulping processes, grinding and refining. In both processes the wood material faces increasing mechanical intensity along its path through the pulping phase (Backlund et al. 2003; Illikainen et al. 2007) and the increasing fatigue enables the fiber material to withstand the maximum intensity in the end of the path. Also other changing properties, as increasing temperature, are essential to succeed in the defibration task.

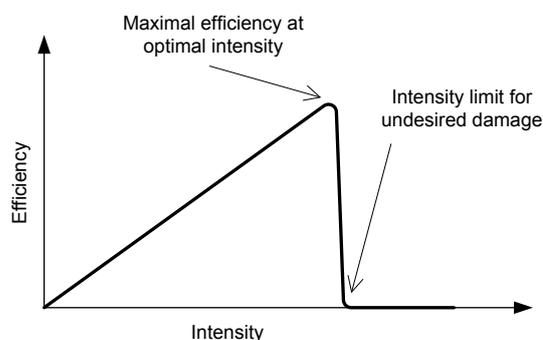


Fig 1. Efficiency as function of treatment intensity (Björkqvist 2011).

This paper revisits the data on wood fatigue published earlier (Salmi et al. 2012b; Salmi et al. 2012a) and combines it with paper property measurements. In this paper, the focus is on the paper and board making aspects of the data. In the following section we present methods of pre-fatiguing, wood material characterization and grinding. Thereafter the effects of fatigue on wood properties, on ground wood pulp, and on paper properties are presented. Finally, we conclude and discuss explanations to the benefits of pre-fatigue.

## Materials and Methods

### Pre-fatiguing

Spruce wood samples (Norway Spruce) were pre-fatigued, i.e. pre-treated by cyclic compression (Lucander et al. 2009). The treatment was carried out to three levels of fatigue: 6000, 12000 and 20000 cycles and cut into  $6 \times 12 \times 12$  (radial $\times$ axial $\times$ tangential) mm<sup>3</sup> cubes with a moisture content of  $45 \pm 5\%$ .

### High strain rate characterisation

The samples were then characterized by the Split-Hopkinson testing technique (Engberg et al. 2009). Stress-strain curves for the samples were obtained by impulsive loading using the encapsulated split Hopkinson device (Holmgren et al. 2008). The device comprised of two long aluminum bars between which the sample was placed. A striker was then fired onto the end of the first bar which caused a pulse to travel through that bar. In the bar-sample interface a part of the pulse was reflected back in the first bar and the rest of the pulse travelled through the sample and into the second bar. How the initial pulse was reflected and transmitted was registered by strain gauges on the two bars. The relation between the transmitted and reflected part of the pulse gave the stress-strain characteristics of the sample. The experimental setup is encapsulated allowing different testing environments such as steam atmosphere, elevated temperature and pressure. Here four testing temperatures were investigated; 20, 65, 100 (steam) and 135°C (pressurized steam). An example of a wood sample between the bars in the encapsulated split Hopkinson device is shown in Fig 2.



Fig 2. A photograph of a wood sample between the transmitter and receiver bars in the encapsulated split Hopkinson device.

### Laboratory grinding

Prior to the grinding trials 2 mm veneer sheets were produced with a Raute lathe. Half of the knotless sheets were processed using the modulated loading device (Lucander et al. 2009) with 20000 compression pulses to both sides of the sample. After that, whole logs, reference veneer sheets and the fatigued sheets were ground with a laboratory stone groundwood (GW) -grinder. Whole logs and veneer were from different trees but both represented typical spruce for groundwood production. Grinding was performed at dry weight contents of  $48 \pm 3\%$  for the reference logs,  $44 \pm 8\%$  for the reference veneer and  $50 \pm 5\%$  for the fatigued veneer. The feed velocity ranged between 0.6 and 1.2 mm/s and cooling water temperature ranged between 66 and 74°C. The resulting pulps were characterized by the specific energy consumption, Canadian standard freeness (ISO 5267-2:2001), fiber length (ISO-16065), laboratory hand sheets (ISO 5269-1:2005), tensile and tear index (ISO 5270:1998).

## Results

### High strain rate characterisation

The stress-strain curves presented in Fig 3 show results from three different testing temperatures; 65, 100 and 135°C. The figure presents wood behavior of reference samples and samples pre-treated with 20 000 compression cycles. The wood samples were impulse loaded at high strain rates and the figure shows the elastic compression region and a part of the plateau region (caused by buckling of the fiber walls into the lumens) for the different samples. It is clear that the wood material was softened both by a testing temperature increase and by pre-fatiguing.

The reason for this should be that the pre-fatigue treatment broke down the wood structure to such an extent that the fiber wall collapse pattern normally occurring at 100°C (reference wood) happened already at 65°C for the pre-fatigued wood. At very low strains the collapse pattern almost resembles the one at 135°C for reference wood. This enhanced ability to collapse should

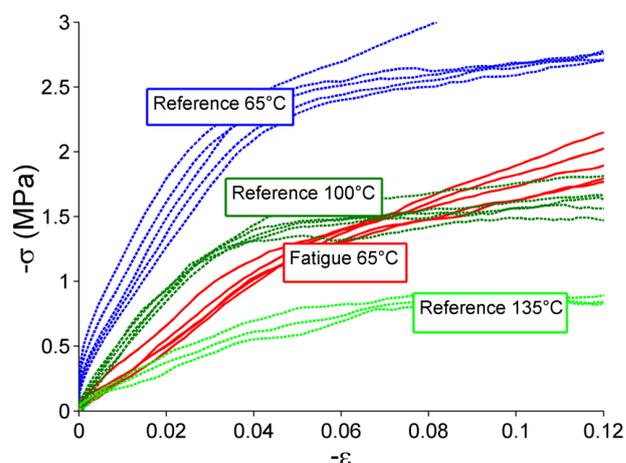


Fig 3. Stress-strain dependence for reference wood and pre-fatigued wood (20 000 cycles). The stiffness of pre-fatigued wood (tested in 65°C) is similar to the stiffness of reference wood at higher temperatures (above 100°C).

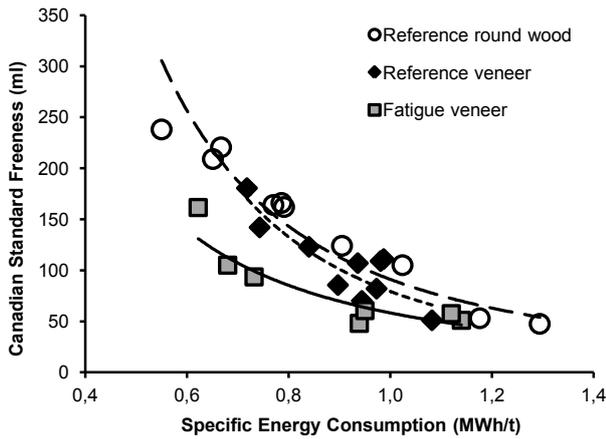


Fig 4. Results from laboratory grinding of whole wood logs and veneer sheets (reference and pre-fatigued) – freeness as a function of specific energy consumption. Each point's uncertainty is estimated to 5%.

prevent major cutting even in harsh environments, e.g. in the groundwood process at high grinding feed velocities of the combing phase. The stiffness of a collapsed fiber is lower than the stiffness of a fiber in its original o-shaped form and can therefore escape the most aggressive grit actions and preserve much of its original length even when one end of the fiber is still bounded to the wood matrix.

**Laboratory grinding**

Fig 4 shows specific energy consumption (SEC) against freeness of the grinding trials in the laboratory GW-grinder. The differences in specific energy consumption between pre-fatigued veneer and references are significant. Approximately 25% less energy was needed to produce pulp with the same freeness from pre-fatigued veneer sheets. The lower SEC is most likely a result of the higher grinding feed velocity that could be used, i.e., higher intensity based on the forward shift of the intensity limit by the pre-fatigue. In addition, the fatigued wood pulp had consistently higher fiber length than either of the references at equal freeness which shows that the shift of the intensity or efficiency limit (Fig 1) was not over utilized by the increased wood feed velocity. Additionally there are indications on a further shift of the intensity limit by a higher grinding zone temperature which appears in the greater challenge to grind fatigued wood probably due to altered thermal conduction properties. Higher fiber length for the fatigued wood pulp than for the reference pulp at equal freeness indicates excellent pliability of the fibers which is promising for the binding and strength properties of the sheets.

Fig 5 and Fig 6 present tensile index and tear index respectively for the paper sheets. As indicated by the fiber length and freeness relationship for the fatigued pulp both the tensile and tear index are developed superiorly compared to respective index development for the references. When comparing pulp production to the same tensile index, Fig 5, the differences in specific energy consumption between pre-fatigued and reference sheets are even larger. Approximately 30% less energy was needed to produce pulp with the same tensile index from pre-fatigued veneer sheets. Good tensile index

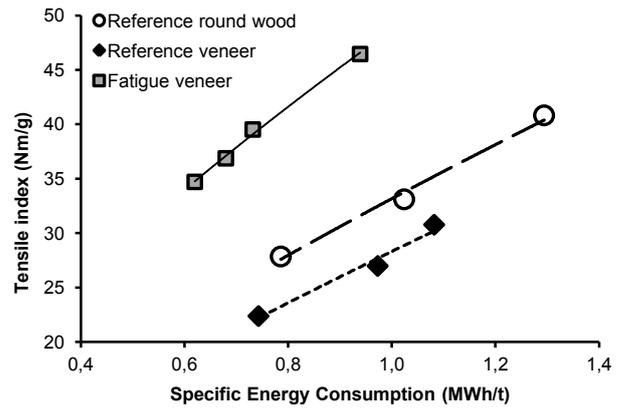


Fig 5. Results from laboratory grinding of whole wood logs and veneer sheets (reference and pre-fatigued) – tensile index as a function of specific energy consumption.

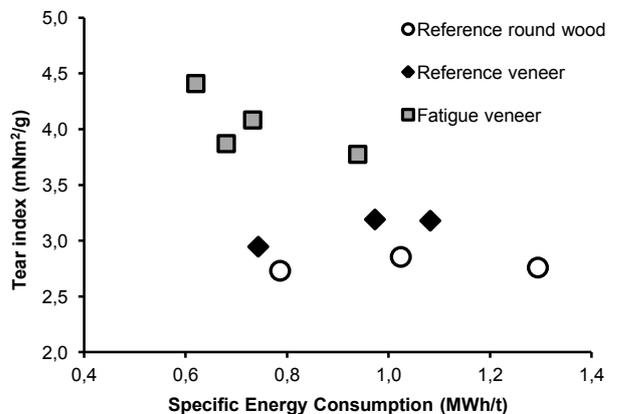


Fig 6. Results from laboratory grinding of whole wood logs and veneer sheets (reference and pre-fatigued) – tear index as a function of specific energy consumption.

development needs flexible fibers to build up a well bonding sheet with high bonding area between the components. Naturally the pre-fatigue has started the flexibility development but the high intensity grinding enabled by the pre-fatigue has developed the final fiber flexibility at low fiber cutting level. Additionally high sheet tensile strength needs high quality fines which have good possibilities to develop in the harsh combing phase at high temperature that enables release of fiber surface layers. To reveal the tensile strength development in detail a more comprehensive study of the pulp is needed.

High fiber length is the major requirement for good tear index development, Fig 6. As in the case of the tensile index the pre-fatigue has enabled production of long fibers even at elevated grinding harshness and at lower SEC compared to the reference cases. Equally high tear development needs production of well bonding fibers and this can be fulfilled as a result of the possibility to produce long fibers at harsh conditions.

The reference veneer was included to show the pure effect of the veneering and the grinding in pure radial stem direction of the wood material. Veneering had positive effects in the SEC-CSF diagram, Fig 4, but not to the same extent as when including pre-fatigue. Surprisingly the veneering procedure had a negative effect on the tensile strength, Fig 5, and a positive effect

of the tear strength, *Fig 6*, compared to the results of the reference round wood. In both sheet strength cases the level of the strength from the reference veneer is although on a significantly lower level than the strength from the fatigued veneer material. Also in this case a more comprehensive study of the pulp is needed to be able to comment the results further.

## Discussion

Warm fatigued wood (tested at 65°C) had markedly lower stiffness and yield point than reference wood tested at the same temperature (*Fig 3*). In addition, the fatigued wood tested at 65°C showed similar behavior as reference wood tested at temperatures between 100 and 135°C. Both fiber wall pre-fatigue and elevated temperature softens the wood material and thereby allows much higher strains before a critical stress-level is reached. The harsher defibration can therefore be used without cutting the fibers which is more beneficial for the energy efficiency. Both in grinding and refining this would mean that a lower temperature during defibration could be used. In refining, a specific energy reduction could be reached when combining the softened material with feeding segments, higher rotational speed and/or smaller plate gaps – to increase the forces acting on the fibers in each impact. Higher forces on the fibers without sufficient softening would lead to fiber cutting. Drastic changes in the operation of the refiner when utilizing softened material can also lead to negative evolution, like increased idling loss consumption with increased rotational speed, which should be dealt with in practical applications.

The pulp produced from pre-fatigued wood had consistently higher fiber length than that produced from the references at equal freeness. An explanation to this would be that the fatigue generation induced cracks between the fibers that made them more easily separable (Salmi et al. 2012b), and fiber length was thus more easily maintained. The effect of pre-fatigue was larger when comparing the pulps to the same tensile index instead of to the same freeness (cf. *Fig 4* and *Fig 5*). Probably, the pre-fatigue treatment also introduced internal fibrillation in the fiber walls which was beneficial for the strength properties of the final paper sheet.

Many previous mechanical pulping studies have shown the importance of high grinding zone temperature for fiber length but also the risk of less fiber surface openings which are important for the fiber bonding ability. On the other hand no practical grinding work is known to the authors where high grinding zone temperature has disabled the opportunity to produce well binding fibers in the harsh combing phase. High zone temperature in combination with worn grinding surface has though hindered the friction work to release fiber material to the extent that an accelerating build up of the zone temperature eventually stops the wood feeding. This represents although extreme case for GW-grinding but is probably a parallel reason for the greater challenge to grind fatigued wood.

Even if both a rise in fiber wall fatigue and temperature make the fiber less fragile, i.e. it can endure higher defibration intensity without fiber cutting, it is obvious that the positively affecting phenomena are different. The first is connected to internal fiber wall opening and the second is directly polymeric material softening with rising temperature. An important sequential difference is that the pliability of the first is present to a major degree and the second to a minor degree afterward at lower temperature when paper is formed of the pulp.

It is also apparent that the softening due to temperature rise forms a flexible surface layer which reacts on mechanical actions differently than surface layers on fibers softened due to internal cell wall openings from mechanical fatigue. This difference affects the formation of fines and external fibrillation which is, in addition to length of slender fibers, important for the sheet bonding properties. Accordingly, from the viewpoint of fines formation, shifting the intensity limit by softening the wood matrix by in-line or off-line fatigue probably produces different pulp quality at high intensity pulping than softening wood by high temperature treatment. The drawback of increasing the intensity limit by fatigue compared to by temperature rise is that fatigue production requires high value energy in the form of mechanical work when heating in principle can be produced with low value heat energy. In practical industrial pulping heating is though also mostly produced with mechanical work through heat dissipation from deformation of the viscoelastic wood matrix. Consequently it is not straight forward how the schematically drawn efficiency curve, *Fig 1*, is exactly formed when the intensity limit is pushed with fatigue compared to with heating of the wood matrix. Finally it can be concluded that heating always appears when producing fatigue by strain variation and therefore in principal there exists an optimal division between fatigue and heat that enable high intensity and high efficiency pulping producing low fiber cutting and slender fibers (high internal fibrillation) with much fiber surface damage (high external fibrillation).

This research is part of basic research on wood behavior in mechanical pulping. For this reason only the defibration action itself has been under interest and accordingly only the energy use during grinding is considered when calculating the SEC. Additionally the energy used for the pre-generation of fatigue was in practice all converted to heat and cooled away before the grinding part of the experiments and was therefore never forwarded to the grinding process. For general interest it can be mentioned that the gross energy used for the pre-fatigue was estimated to 12 MWh/t. Most of that is however fatiguing apparatus losses. Industrial processes utilizing in-line or off-line fatigue should naturally consider all energy use.

The utilization of fatigue was in this research applied in the grinding process due to a clear realization based on the quite deterministic path of the wood material in this process. There is however no principal obstacle to utilize fatigue in a similar way in the refining process. If applied in the pressure groundwood process a probable advantage can be achieved in the SEC and in the pulp strength. The strength advantage can however also be gained by raising

the grinding zone temperature. If on the other hand applied in the groundwood process the same advantages can be achieved but in this case the other enhancing alternative is not possible as the temperature cannot be raised in the open process.

## Conclusions

Pre-generated fatigue can reduce the grinding energy with as much as 25% when ground to similar paper quality. The effects of fatigue extend beyond the small strain regime (0-1% strain) up to the buckling at the plateau region of the stress-strain curve (5% of strain). Grinding of fatigued wood produced long fibers which could be liberated from the wood matrix with ease.

Warm pre-fatigued wood had similar mechanical properties as hot native wood. Both pre-fatigue treatment and high temperatures softens the wood material allowing larger strains before a critical stress-level is reached which mean that harsher defibration (higher intensity) can be exploited. As higher temperature is known to improve ground wood pulp quality we argue that pre-fatigue works in a similar way. Additionally pre-fatigue is beneficial for the strength properties of the final paper.

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