Dynamic Compression: A Novel Technique to Reduce Energy Consumption during Wood Fiber Production

Alejandro Martínez-Conde,[a,*] Daniela Huber,[b] Stefan Pinkl,[c] Eike Mahrdt,[a] Alfred Teischinger,[a] and Ulrich Müller [a]

Thermo-mechanical refining is a common fiber production process known for its high energy demands. Throughout this process, wood chips are subjected to repetitive shearing and compression such that the fibers separate and subsequently fibrillate. There is a growing body of research in the development of mechanical pre-treatments that reduce energy demands during chemo- and thermo-mechanical pulping, with shear/compression combinations currently standing as the most efficient method of initiating defibration. Given the common grounds between the fiberboard and paper refining processes, it could be possible to use paper pre-treatments during fiberboard pulp refining. Furthermore, as pulping fibers for fiberboard are less worked and refined, mechanical pre-treatments are assumed to be more efficient. In this study, the effectiveness of dynamic compression was assessed as a pre-treatment step before the chips enter the refiner. Shaped wet chips with an annual ring orientation of 45° were struck by a free-falling weight with a fixed potential energy using a special prototype. After refining both the reference and pre-treated chips using a pressurized disc refiner, the energy consumption of those fibers was 48% lower than that for non pre-treated chips for a comparable fiber quality.

Keywords: Chip pre-treatment; Cracks; Dynamic compression; Energy reduction; Fiber production; Smashing; Refiner

*Contact information: a: Institute of Wood Technology and Renewable Materials, University of Natural Resources and Live Sciences, Vienna, Austria; b: Institute of Environmental Biotechnology, University of Natural Resources and Life Sciences, Vienna, Austria; c: Wood K plus –Competence Centre for Wood Composites and Wood Chemistry, Linz, Austria; *Corresponding author: alejandro.martinezconde@boku.ac.at*

INTRODUCTION

The most common process for refining wood fibers involves the use of pressurized disc refiners, producing thermo-mechanical pulps (TMP), including those used for fiberboard pulp (Walker 1993). Chemo-thermomechanical pulping (CTMP), on the other hand, is commonly used for board and papermaking, where chips are chemically pre-treated with sodium sulphite, supporting good strength of the pulp, and sometimes bleached before refining (Walker 1993). Thus, there is a thermo-mechanical process common to both papermaking and fiberboard pulps. These processes, using pressurized disc refiners, can be divided into three main categories: i) chemo-thermomechanical pulping, which is mainly used for board and tissue (bleached and unbleached); ii) thermomechanical pulping, mainly used for printing and writing paper as

well as for board; and iii) thermomechanical pulping for fiberboard production. Thermo-mechanical pulp refining requires lower operating temperatures, and the resulting fibers are more refined and fibrillated (increasing their bonding ability). In addition, TMP fibers are separated by cell walls, rather than by middle lamellas (Htun and Salmén 1996). However, this technique is associated with a high energy demand, particularly during TMP, and an even higher energy demand during CTMP for a comparable freeness level.

For fiberboard pulps, the energy consumption reaches 200 to 250 kWh/ton for bone-dry softwood (Walker 1993), while for TMP these values do not exceed 2.0 to 3.5 MWh/ton for freeness levels of 120 to 20 CSF (Viforr and Salmén 2005). These values are not far from those published by Nelsson *et al.* (2012), who refined spruce using between 1.7 and 2.15 MWh/bdt with chips pre-treated by an Impressafiner and untreated ones. Similar values are common for newsprint, approximately 2 MWh/ton (Uhmeier and Salmén 1996), and are considered the general value for TMP (Walker 1993). The high energy demand linked to TMP pulp production is currently considered a major technological limitation, particularly when considered in the context of the current increasing trends in energy prices and the tendency to reduce the energy input to reduce costs by increasing process efficiency (Uhmeier and Salmén 1996; Bergander and Salmén 1997; Viforr and Salmén 2005; Viforr and Salmén 2007a; Nelsson *et al*. 2012).

The preferred dimensions of wood chips for the TMP-process are from 18 to 32 mm in length and from 8 to 10 mm in thickness (Walker 1993). Furthermore, a homogeneous size distribution and low fines content are required to produce good pulp strengths (Brill 1985). Chips and water are fed into the refiner and subsequently shredded into a coarse mix of pulp and shives, which is then refined by passing the mixture through two discs separated to create a coarse and a fine bar filter (Atack *et al*. 1994). A high energy input is required to separate and fibrillate wood fibers, resulting in flexible fibers that are capable of becoming highly bound together (Salmén *et al*. 1985; Uhmeier and Salmén 1996; Viforr and Salmén 2005; De Magistris and Salmén 2006; Viforr and Salmén 2007b). In short, the lumen is collapsed by the compression and fibrillation produced by shearing during the refining process (De Magistris and Salmén 2005). However, very few fibres show a collapsed lumen for TMP refining, and in fact, TMP refined fibres are fibrillated, increasing the flexibility of the fibre wall and producing fines of different quality. This effect is well illustrated in the experimental work of Huang *et al.* (2012). The energy demands are specifically linked to compression, when the material is subjected to fatigue. At this point, energy is transferred to heat as the material absorbs large amounts of plastic and viscoelastic deformations, only partially producing structural changes (*Salmen et al.* 1985). This explanation was supported later by the results of Uhmeier and Salmén (1996), which also demonstrated that a large number of compressions on wood specimens do require large amounts of energy to achieve any remarkable effect on the plastic strain and plateau stress levels. Subsequent studies from Bergander and Salmén (1997) showed that radially compressed wood does not exhibit any cracks after a cyclic loading, but presents a weakening zone in the cell corner regions. Furthermore, De Magistris and Salmén (2005) concluded that the same degree of deformation is obtained through combined compression and shearing loads as with pure compression alone; however, for the same deformation level, compression requires double the energy.

Efficient fiber collapse can be achieved with small amounts of shear when

combined with compression, increasing the bonding strength of the fibers and also reducing the energy consumption during the refining process (Viforr and Salmén 2007b). Furthermore, the tensile index from treated and untreated fibres showed higher values at 90 °C with a low pretreating speed (10 mm/s) (Viforr and Salmén 2007b). Similar studies assessed whether high amplitude pre-compression (Salmén *et al*. 1985) and combined shear and compression as chip pre-treatments (Viforr and Salmén 2007a) could help to reduce the energy consumption during refining. Salmén *et al.* (1985) found that the structural breakdown of wood is improved by increasing the temperature. Several other studies also investigated how to reduce energy demands while increasing the fiber collapsibility (Sabourin 1998; De Magistris and Salmén 2005). Gorski *et al*. (2010) summarized in their review all mechanical pre-treatments of wood chip to that date. However, many of the studies cited in Gorski *et al*. (2010) do not specify whether the energy reduction also takes into account the additional energy used during pre-treatment. Nonetheless, there are several published examples where some of these pre-treatments significantly reduced overall energy demands. Thus, Björkqvist *et al*. (2012) showed that pre-fatiguing veneer sheets reduced the grinding energy required to produce the pulp by 25% while maintaining the level of freeness. Viforr and Salmén (2007a) also showed that pre-treating approximately 2 mm-thick spruce pieces saturated at 90°C using a shear and compression device saved around 100 kWh/ton for tensile indices between ~6 and ~11% (a value estimated from the graphics presented in the article). Combining shear and compression has been found to be the most effective method of mechanically pre-treating wood chips in order to reduce energy consumption; in addition, this effect is more evident at 90°C with highly deformed cell walls (De Magistris and Salmén 2006); consequently, many studies have assessed the effectiveness of Impressafiner (Andritz, Austria), a type of compression screw with a high compression ratio and high temperature and pressurized conditions that consumes between 20 and 40 kWh/ODT (Oven Dry Ton) (Sabourin 1998). This equipment has been reported to achieve energy reductions on the order of 20% (Sabourin 1998) and 6% (Nelsson *et al*. 2012). Nelsson *et al*. (2012) also showed images of the chips treated with the Impressafiner that clearly illustrated partial disintegration with multiple cracks along the longitudinal axis of the treated chips. Hellström *et al.* (2012) developed a new pre-treatment method known as the "collimated chipping", able to produce chips prone to induce directed cracks. In this method, the chips are processed using a spout angle (and angle between the cutting direction and the wood fibre direction) of 50°. This process damages the chip reducing the energy consumption during the refining process by ~15% (Hellström 2012). This method presents several advantages including an increment in the packing density of the chips in the digester and improving impregnation of chips using chemicals. There are few novel processing techniques currently used in industry, including advanced thermomechanical pulping (ATMP; Andritz, Austria). In ATMP, a pressurized Impressafiner and a low specific energy refiner are combined in a pre-treatment to further reduce the energy used in the overall process, among other advantages. In March 2011, UPM Kymmene (Steyrermühl, Austria) installed first system of this type.

Despite the large body of information on the influence of mechanical compressive pre-treatments on energy consumption, there is almost no information on the effect of shock waves on wood materials as an alternative disintegration method. Shock waves constituting an abrupt increase in pressure can be created using strong explosions and

have great industrial applicability, *e.g*., in metal welding (Kalpakjian and Schmid 2010). If the pressure of a shock wave striking a material exceeds its yield strength, the material disintegrates into dust (Píriz 2015). In other words, when the energy density of the shock wave, defined as the energy stored within the volume of air displaced by the wave, surpasses the pressure the material can stand, the material breaks. However, little is known about the effect of shock waves on wood materials. Itoh *et al*. (1998) studied the impact of underwater shockwaves on the internal structure of Sugi wood, which can fracture its bordered pit membrane and increase its permeability. They found that high-energy shock waves were able to break the internal structure of the wood material. These results open up the possibility of an intermediate type of shock wave, impacting the material but not causing complete disintegration, as a pre-treatment during the initiation of defibration.

In this work, the effectiveness of the dynamic compression created by shock waves as pre-treatment before defibration was assessed. This paper describes a prototype device specifically designed for this purpose. Identically shaped chips from rings with a 45° orientation were used, and the impact of such shock waves on the deformation of the wood material and on the overall energy consumption for the full refining treatment were evaluated.

EXPERIMENTAL

Materials

Industrial wood chips vary widely in their sizes and shapes. Thus, in this study, identically shaped chips were used to reduce experimental variability. The shaped chips were produced from fresh Austrian spruce wood (*Picea abies*), a species commonly used in the European wood industry. The sapwood was mechanically cut using a circular saw into chips 40 mm long, 25 mm wide, and 5 mm thick. The predominant ring orientation was an angle of approximately of 45º (Fig. 1).

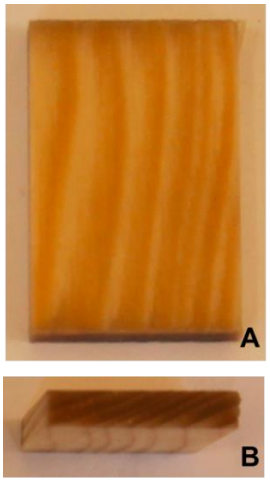

Fig. 1. Shaped wood chips with a predominant 45º-year ring orientation: A) top view; B) front view (thickness)

This angle was selected because it is the most common annual ring orientation observed in industrial chips from drum chippers. After the oven-dry weight and moisture content of the chips were measured, they were soaked in tap water at ~20 °C during the 24 h before treatment. This procedure was applied to all treated (dynamically compressed) and untreated (control) chips.

Due to the high production costs linked to obtaining uniformly shaped chips, and in order to test the reliability of the measuring energy device installed in a lab-scale refiner, industrial commercial-sized chips of Austrian spruce were also refined. Oversized chips were removed, and the remaining chips were stored outdoors at an average temperature of -2 °C and a humidity of 75%. Within the lab facilities, ambient humidity was considerably lower, reducing the moisture content of the industrial wood chips from 79% to 58% prior to refining. Before refining, no chip dimension exceeded 24 mm in any direction (transversally, longitudinally, or radially). In total, approximately 4 kg ODW (oven-dry weight) of material was used in each control experiment.

Methods

Dynamic compression or "smashing effect"

During compression, the specimen experiences the amount of energy transferred from the work of the external forces producing the deformation. At small loads, the specimen experiences non-plastic deformation. However, shearing stress rapidly appears in specimens exposed to isotropic compression forces. If the load is large enough to exceed the critical shear stress supported by the material, macroscopic breaking up of the specimen occurs. In the present experiments, a device was used that was designed to subject wood chips to high pressures over short periods of time; this was termed the "smashing effect". Chips at ambient temperature (20 °C) were individually placed on a flat surface and were struck axially by the flat rigid surface of a cylindrical body weighting 22.6 kg. The energy produced was empirically adjusted to the shape of the chips used and considered enough to treat most of the chips. Thus, the kinematic energy was estimated to be 54 J/g for the ODW material (108 J per 2 g ODW chip), or 15 kWh/t ODW. At higher energy levels the chips completely disintegrated into dust, while at lower levels no alterations to the chip structure were detected.

A 45°-year ring orientation falls at the midpoint between 0º, which shows a densification response to the pressure, and 90º, which represents disintegration. A 45º-year ring orientation seemed likely to maximize shear stresses, as it is also the predominant angle in industrial wood chips.

Dynamic compression equipment device

The prototype dynamic compression device used in this study is hereafter referred to as the "smashing tower". This device consisted of a metallic free falling cylinder that struck a flat anvil with a pre-set kinematic energy, following the basic physics principle of a free falling body.

The falling cylinder was guided by a PVC pipe with pierced holes (diameter, 10 mm) to diminish the compression of air caused by the falling body. The anvil was placed over a thick layer of sand, which absorbed the residual energy so the falling body did not kick back. The base of the smashing tower was surrounded by a wooden structure made of a 3-ply tableforms and solid wood pieces glued vertically and mounted over a steady

surface. During each test, the falling cylinder was raised manually using a pulley set at the top whose height was set using cross rods. The height between the bottom of the free falling cylinder and the anvil's surface was measured to precision using a laser. Fig. shows a schematic drawing of the device and the principal parts involved in the process.

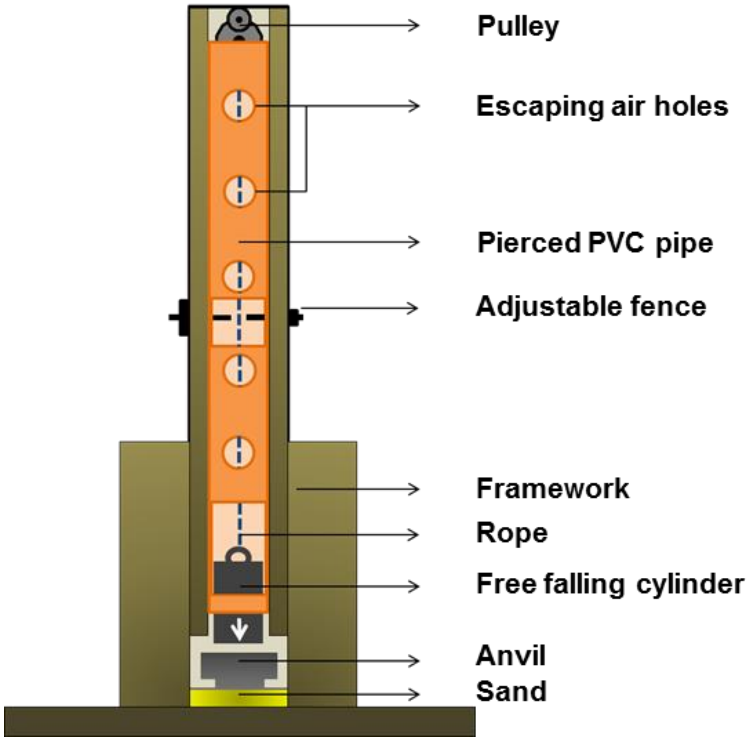

Fig. 2. Schematic drawing of the device used for dynamic compressions ("smashing tower")

Using gravity drop hammers, advantage could be taken of the energy derived from the free falling ram (a process known as drop forging). The energy available from a drop hammer is the product of the ram weight and the drop height (Kalpakjian and Schmid 2010). Thus, the potential energy of the falling body (assuming any loss of energy by friction and air resistance is negligible) can be calculated as follows,

$$E_p = m \cdot g \cdot h \quad (1)$$

where E_p is the potential energy (J), m is the mass (kg), g accounts for gravity (m/s²), and h is the vertical height (m).

The strike surface must be completely parallel to the surface of the anvil to facilitate the transfer of the potential energy into the chip. A leveler was used to check that the chip was parallel to the anvil before the impact. In addition, polymer clay was impacted before the test to check whether the expected level of deformation could be observed after the impact. During the previous tests, a "hand-fan effect" was observed on the smashed chips, where the lower side remained mainly unaltered and the upper side spread out whenever the surface of the cylinder was not adjusted into position.

Refining

The reference (untreated) and dynamically compressed pre-treated chips (smashed chips) were subsequently refined in a 12" discontinuous single disc laboratory refiner from Andritz (Graz, Austria). D2A505 unidirectional discs with 3 bar lines (passage width dimensions = 7 x 4 x 1 mm) were used. The motor of the refiner was a three-phase asynchronous motor, weighing 250 kg, with a power factor of 0.84, a rotational motor speed of 1465 rpm, and a maximum power of 45 kW. Before the refining process, the refiner was heated to 165 °C, and the milling gap was adjusted to 0.2 mm. This refiner does not work continuously, and therefore, chips were first placed in a pressurized vessel for ~3 min with a pressure of 7 bar (700 kPa). During this time, the temperature increased from 135°C steeply up to 165°C, the latter being the set refining temperature.

Power measuring device

The apparent power consumed was measured using three AC Current transducer AT100 B420L from LEM (Fribourg, Switzerland) devices linked to a universal converter for voltage RMS values CAIS-UNI-RMS-V 110 (ABB, Zurich, Switzerland) and to a DC Power supply ML30 (Puls, Munich, Germany) mounted within the refiner, and attached to a Data Acquisition Module 4017 (ADAM, Milpitas, USA). The power consumed was measured in W·s.

Energy consumption analysis

To compare the specific energy consumed during the refining process between the reference and pre-treated chips, all the power consumed during other associated processes (non-refining steps) was also subtracted. This final value was defined as the power load. The apparent power used during the refining process was transformed into true power, measured in Watts (W), and was used to calculate the total energy consumption per unit of time. Finally, the total energy consumed was divided by the ODW mass of the refined product in kilograms to estimate the total specific energy consumption (SEC). Thus, all SEC values in this article refer to the ODW mass.

Scanning electron microscopy (SEM)

The reference and smashed chips were also analyzed using a Hitachi TM 3030 Tabletop Microscope (Maidenhead, UK) Scanning Electron Microscope (SEM). All the chips were dried prior SEM observation, and the samples were imaged under vacuum conditions.

Production and testing of MDF lab-scale boards

With the remaining fiber material, several MDF lab-boards were produced. The dimensions were 28 x 28 cm^2 (area) and 14 mm (thickness) and with a target density of 0.7 g/cm^3. The fibers were resinated in a rotating drum with an airless spray gun (EOS 30-C25 Kremlin Rexson, United Kingdom) and a nozzle fitted with 40° spray angle and 18 µm diameter with a 10 MPa of outlet pressure. The resinated fibres were evenly spread into a wooden box and manually prepressed. Finally, the mat was pressed at 200°C for 168 s using a laboratory press (Langzauner, Austria). Several mechanical properties were tested according to the following standards: MOE for bending (EN310 1993), thickness swelling (EN317 1993), and internal bonding (EN319 1993).

Sieve analysis

The diameter (width) of the refined fibers was classified using a sieve analyzer with the following mesh sizes: 2 mm, 1.4 mm, 1 mm, 800 µm, 600 µm, 400 µm, and 200 µm following the DIN 66165-2:2016-08, using sieves 25.4 x 203.2 mm diameter. After a pretest, 3 g of ODW material was considered appropriate for the sieve analysis, with each test being conducted using this amount. Each test was repeated three times. The main advantage of this method was that only the width of the fibers had to be measured.

Statistical analyses

A t-test was used to check whether the energy consumed during the pre-treatment and treatment process varied overall between the reference and pre-treated chips. A Saphiro-Wilk test was used to check whether the data were normally distributed. A Levene's test was also used to check whether the variance among samples was homogeneous. The statistical tests were performed in the statistical software SPSS (IBM, Armonk, NY, USA), and the results were considered significantly different for p-values < 0.05.

RESULTS AND DISCUSSION

Effect of Dynamic Compression on the Wood Chip Structure

Before the test, all chips showed similar structural characteristics: oven-dry weight (ODW) of 2.08 g, coefficient of variation of 5%, and moisture content of 78%. Thus, it was expected that the wood chips used had lower influence on the variability of the results obtained.

After being exposed to a powerful dynamic compression, the integrity of the chips was compromised. Figure 3 shows the effect of the dynamic compression on the chip surface under dry and wet conditions. The small cracks observed in the surface of the chips were due to the circular sawing mechanism used to custom-size the chips. At a magnification of 30X (Fig. 3A1), these cracks were not noticeable in the reference chips, although they become increasingly obvious as the magnification power increased (Fig. 3A2 and A3).

Densification was also observed on the surface of the smashed dry chips (Fig. 3B1), whereby fibers were crushed and stacked together, and as a consequence, the circular sawing cracks were not apparent. In addition, if the potential energy of the free falling body was not high enough, the latewood collapsed, but the early wood was still destroyed, reducing the thickness of the chips. In contrast, the level of disintegration of the wet chips following the pre-treatment was consistently large (Fig. 3C1).

The presence of macro and micro-cracks was seemingly distributed at random across the chip surface, sometimes distributed in different zones. This follows the description by Gerhards (1982), who showed that moisture content influences the mechanical characteristics (*i.e.*, strength and stiffness) of the wood. Thus, due to the appearance of cracks and the possible differences in moisture content among chips, all tests were performed on soaked chips.

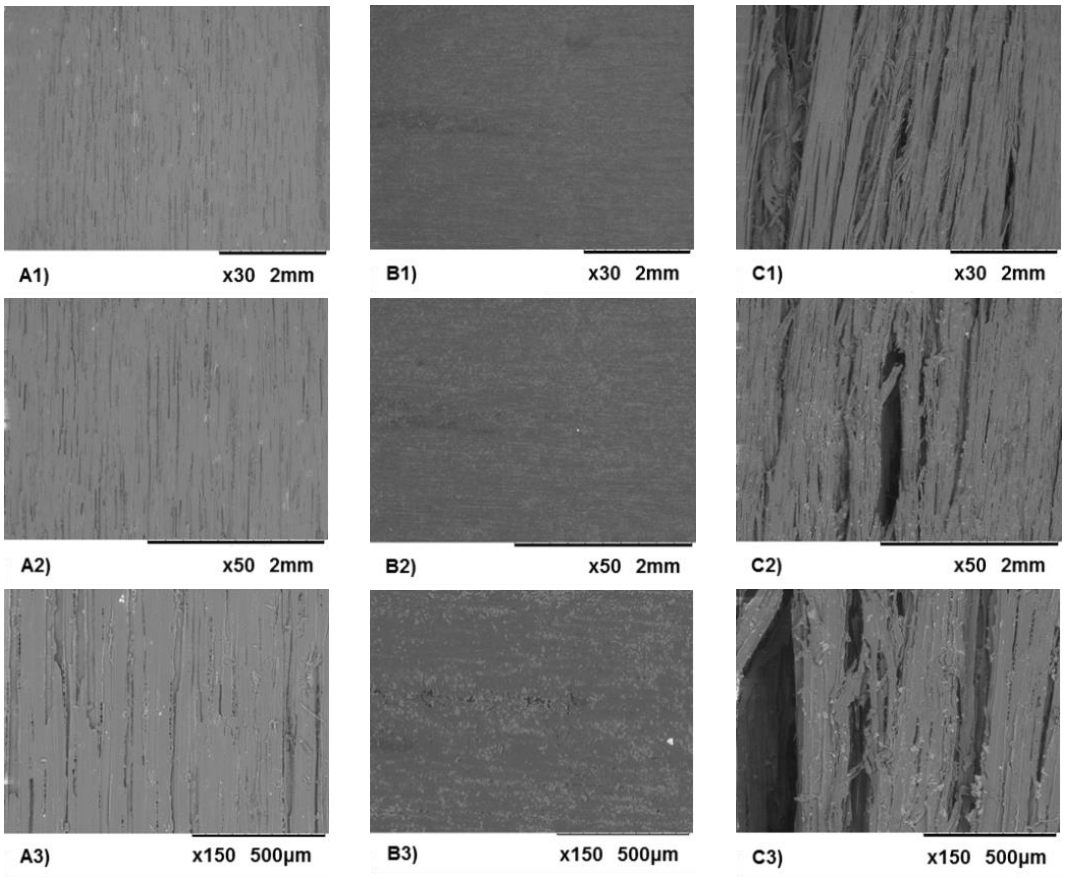

Fig. 3. Structural differences among the surfaces of different reference and smashed chips, for wet and dry chips observed under a SEM: A) Reference chips: A1) 30X, A2) 50X, and A3) 150X magnifications; B) Smashed at 20°C oven-dried chips (103 ºC, 24 h): B1) 30X, B2) 50X, and B3) 150X magnifications; C) Smashed at 20°C wet chips (MC 78% during treatment): C1) 30X, C2) 50X, and C3) 150X magnifications

Fig. presents micrographs taken with a SEM of the reference and pre-treated wet chips before refining, showing evident differences between the two types of chips at different magnifications.

The effect of the dynamic load on the chips was clearly visible on the surface. Cracks appeared in the longitudinal direction, parallel to the grain. Macro-cracks or macro-ruptures appeared in a random distribution over the surface. Their penetration depth could not be easily measured, but occasionally they penetrated up to 100% of the thickness of the chip (representing a complete breakage of the chip into smaller pieces). Fig. 4B3 shows a clear example of a deep crack that increased flexibility of the specimen, even allowing folding.

Pre-treated chips showed observable characteristics similar to those shown by chips pre-treated using an Impressafiner (Nelsson *et al*. 2012), supporting the expectations of a reduction in the energy required to refine this type of chip.

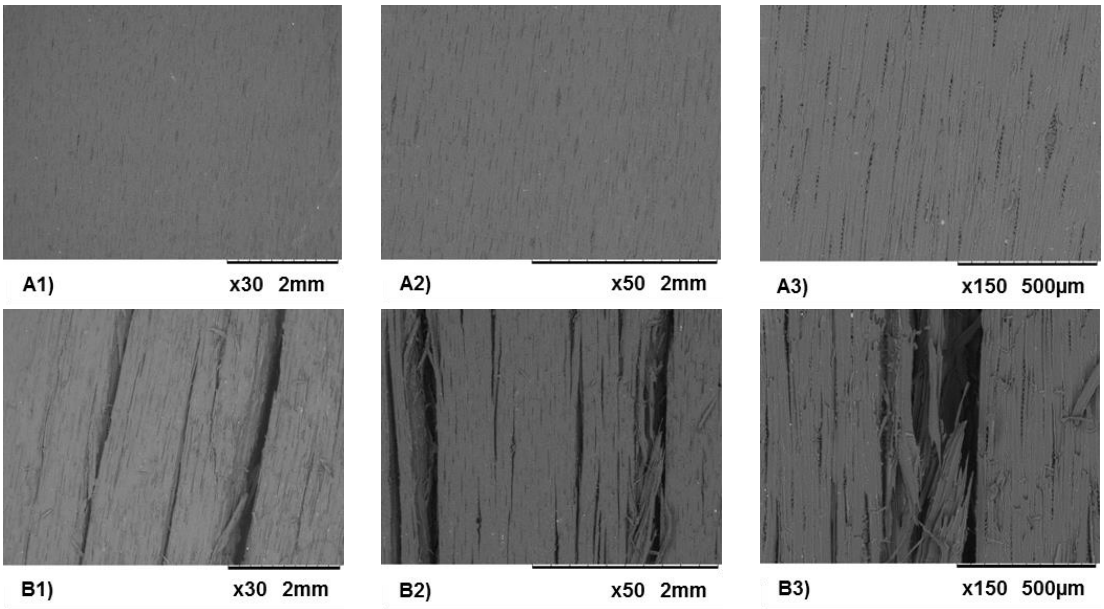

Fig. 4. Structural differences between reference and smashed chips observed using a SEM, where pre-treated chips were smashed under wet conditions (MC 78% during pre-treatment): A) Reference chips: A1) 30X, A2) 50X, and A3) 150X magnifications; B) Smashed chips at 20°C: B1) 30X, B2) 50X, and B3) 150X magnifications

Refining Energy Consumption

Figure 5 shows a temporal variation in power usage between reference chips (not pre-treated) and pre-treated chips throughout the entire process. The power load is inherent to each refining process, with a coefficient of variation (CV) of approximately 1%. Within tests, the apparent power at the baseline also showed a CV of approximately 1%. In general, the energy used for refining the reference chips showed higher variability compared smashed chips (Fig. 5). This is important to consider when assessing the level of energy reduction during TMP.

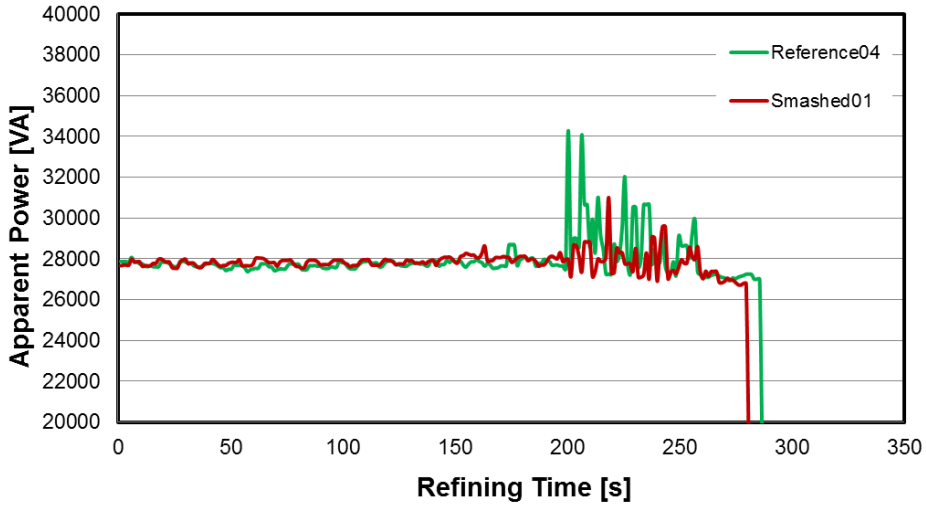

Fig. 5. Apparent power throughout the refining process of an example reference chip (light green line) and a pre-treated chip (dark red line)

The graph shows clear differences in the apparent power load during engine loading (0 to 200 s approximately), which was linked to the refining process (200 to 250 s, approximately). The energy consumption during engine loading was subtracted from the calculations, as it was not influenced by the type of chip used. Table shows the results from the paired refining tests using reference and pre-treated chips.

Table 1. Refining Parameters Measured during Paired Tests with Reference and Pre-Treated Chips

Test	Refining Energy (J)	Dry Mass (g)	Specific Energy Consumption (J/g)	Refining Time (s)
Reference01	86568	405	214	57
Reference02	69126	349	198	64
Reference03	106825	376	284	57
Reference04	84876	353	240	66
Pre-treated01	43016	333	129	66
Pre-treated02	44172	290	152	64
Pre-treated03	48249	379	127	63
Pre-treated04	17500	221	79	48

The refined masses shown in Table 1 differed slightly among the treatments due to small differences in moisture content among the samples. SEC, on the other hand, is presented as energy consumption per ODW kilogram of refined material, resulting in a comparable measurement. Table 2 shows the descriptive statistics and normality test for the reference and pre-treated chips. For both types of chips, normality can be assumed ($p > 0.05$), and parametric tests to analyze whether the level of energy consumption differed between reference and pre-treated chips were thus appropriate.

Refining the pre-treated chips used 112.32 J/g less energy than did refining the reference chips, representing a reduction in energy consumption of about 48% (Fig. 6).

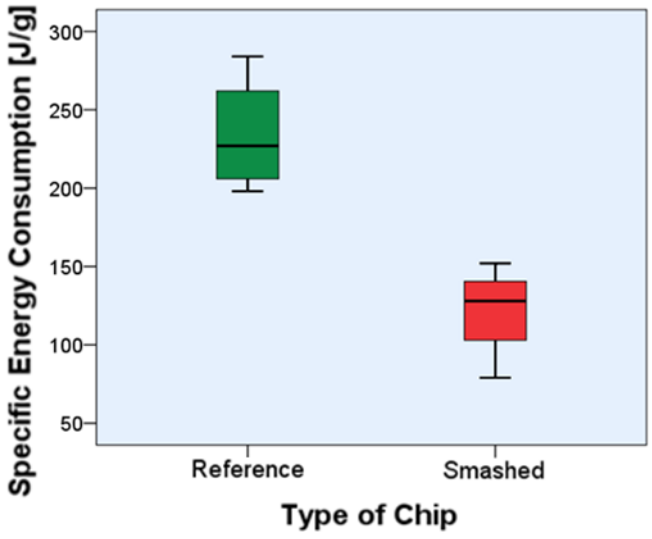

Fig. 6. Specific energy consumption box plot for reference and pre-treated chips

Table 2. Descriptive Statistics Normality Test for Specific Energy Consumption Variables for both Reference and Pre-Treated Chips

		Descriptive Statistics				Shapiro-Wilk		
Specific Energy Consumption (J/g)	Chip Type	N	Mean	Std. Deviation	Std. Error Mean	Statistic	df	Sig.
	Reference	4	234.000	37.559	18.779	0.951	4	0.720
	Pre-treated	4	121.750	30.674	15.337	0.904	4	0.449

Table 3 shows the results of the Levene's test, to assess whether the distribution of the variance was homogeneous between the samples, and the t-test, to check whether the energy consumption differed between the reference and pre-treated chips. The Levene's test returned a p-value > 0.05, suggesting that the data followed a normal distribution with homogeneous variance; consequently, a parametric t-test to check for differences between reference and pre-treated chips was appropriate. The two-tailed t-test returned a p-value < 0.05, indicating that the mean specific energy consumption during refining differed significantly between reference and pre-treated chips. Thus, pre-treating chips with dynamic compression reduced energy consumption by 48%.

Table 3. Levene's Test and Student's T-Test for Specific Energy Consumption between Pre-Treated and Reference Chips

Specific Energy Consumption (J/g)	Levene's Test for Equality of Variances		T-Test for Equality of Means						
								95% Confidence Interval of the Difference	
	F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Equal variances assumed	0.252	0.634	4.630	6	0.004	112.250	24.247	52.921	171.579
Equal variances not assumed			4.630	5.770	0.004	112.250	24.247	52.342	172.158

Considering the potential energy transferred to the chip during the pre-treatment (54 J/g), the actual energy reduction was approximately 25%. This reduction is comparable to those reported for other techniques associated to TMP, *e.g.*, Sabourin (1998), who reported a reduction of ~20% using an Impressafiner; Viforr and Salmén (2005), who obtained a reduction of ~25% using wood shavings instead of normal chips; Viforr and Salmén (2007a), who achieved an energy reduction of 100 kWh/ton (estimated as ~11%) in the total electrical energy consumption by using a shear and compression pre-treatment; and Björkqvist *et al*. (2012), who also achieved an energy reduction of 25% using a fatiguing pre-treatment without compromising paper quality. The higher percentage achieved here possibly relates to the fact that for fiberboard pulp

production, fiber property is not a main requirement (Salmén 2014), and fibers are generally less refined.

These results provided solid evidence on the effectiveness of pre-treating the chips using dynamic compression in the overall SEC during refining. To check whether the energy reduction was directly related to the pre-treatment and not to any other potential confounding variable, a check for potential correlations between variables was performed. The Pearson's correlation coefficient, which measures the level of linear correlation between two variables, showed a significant correlation ($p < 0.05$) between the refining time and the refining energy for pre-treated chips. No other significant correlations were found. The present study was based on four independent tests; therefore, further studies would be required to assess the influence of refining time as a potential confounding variable.

In addition, Table 4 shows the refining parameters for each of the individual tests performed with the reference industrial chips. These parameters were used to assess the reliability of the energy-measuring device, and to compare the levels of energy consumption between the refining of real industrial chips and idealized untreated chips. The mean value of the SEC for the industrial chips was 249.80 J per kg of ODW with a standard deviation of 49.38 J/kg ODW.

Table 4. Refining Parameters for Reference Industrial Chips

Test	Refining Energy (J)	Dry Mass (g)	Specific Energy Consumption (J/g)	Refining Time (s)
Reference01	1166079	4430	263	152
Reference02	1033218	3867	267	142
Reference03	1207284	4667	259	158
Reference04	1193786	4294	278	155
Reference05	888317	5036	176	216
Reference06	1242138	4268	291	221
Reference07	1254651	4403	285	221
Reference08	798910	4459	179	296
Reference09	852467	4487	190	299
Reference10	1436749	4636	310	270

A Pearson's correlation analysis was also performed to determine whether refining energy, dry mass, and refining time were correlated for industrial chips, and the results showed no significant correlations ($p > 0.05$). A normality test showed that the SEC values were normally distributed ($p > 0.05$), allowing the use of parametric tests for further comparisons.

To check whether SEC measurements were reliable, a t-test was used to look for differences between industrial and shaped reference chips. Neither the Levene's test nor the t-test showed any significant differences ($p > 0.05$). Thus, it could be assumed that the variances were similar and that SEC did not differ between reference industrial and shaped chips. The differences in SEC during refining for the industrial and shaped chips can be also found in Fig. 7 which also shows how industrial chips presented a much larger variability than shaped chips, possibly due to the much larger variation in shape and sizes found in industrial chips.

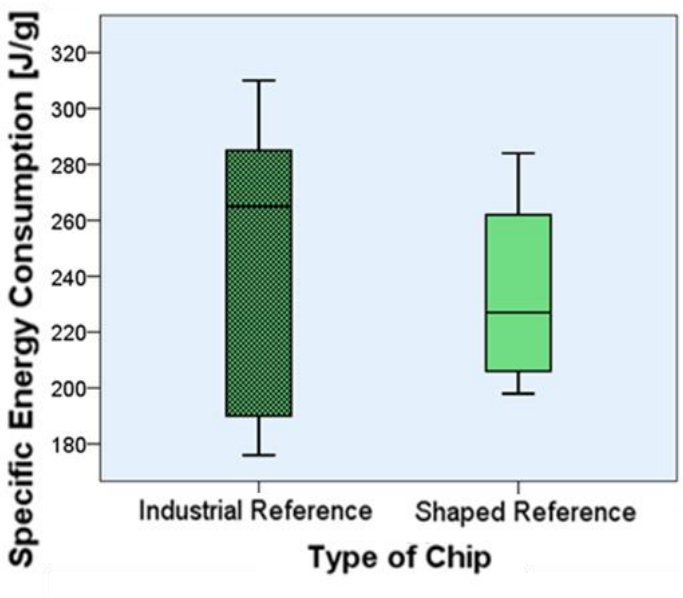

Fig. 7. Boxplot showing specific energy consumption for industrial and shaped chips

Fiber Characterization

Energy reduction in TMP can be usually associated with specific mechanical properties of the resultant fibers. However, evaluation of fiber quality for fiberboard pulp tends to be carried out by expert personnel through tactile and visual evaluations (Benthien *et al*. 2013). Conventional fiber dimension detecting systems for TMP cannot analyze the fiber properties of fiberboard pulp (Benthien *et al*. 2013), specifically because fiber dimensions are measured as i) very small particles (fines), ii) single fibers, iii) fiber bundles (shives), and iv) undefibrated wood particles (Benthien *et al.* 2013). Consequently, in this work a new method was developed to evaluate fiber properties for fiberboard pulp, as described below.

Tactile and visual evaluation

This evaluation was conducted by workers and research experts in the field and involved the analysis and comparison of fibers from reference and pre-treated shaped chips. These experts could not identify any remarkable differences between the two types of fibers, although fibers from smashed chips appeared to be softer to the touch and gave the impression of being more refined.

Production and testing of MDF-lab-scale boards

MDF lab-boards produced with the resultant fibers were produced and tested following the standards described before. Table summarizes the results from these tests. The mechanical properties did not seem to differ between these two board types, which were produced using reference and pre-treated fibers.

The thickness swelling did differ, with water uptake decreasing after 24 h for pre-treated fibers. However, these boards were produced using laboratory devices, and the process does differ from the industrial MDF production process.

Table 5. Comparative Analysis between MDF Boards made from Reference and Pre-treated Shaped Chips

Raw Material:	Mean Density (kg/m³)	IB (MPa)	Thickness Swelling after 24 h (%)	Water Uptake after 24 h (%)	F_{max} Bending (N)	MOE (MPa)
Reference	554.36 (12)	0.1 (15)	34.81	33	282.97 (2)	1130.45 (1)
Pre-treated	567.38 (5)	0.1 (16)	25.17	29	246.58 (17)	1191.75 (3)

(*) is the coefficient of variation

Sieve analysis

The results are shown in Tables 6 and 7. In addition, Fig. 8 corresponds to the summary values from these tables. The main difference found was in the weight of the material retained in the pan, which was higher for fibers from pre-treated chips. Furthermore, the fiber width for the reference fibers seemed to be slightly higher for large particle sizes. These results could be explained by the smashing effect, as fibers were broken into small pieces, and some small particles appeared during the refining process which possibly corresponds to the fines content.

Table 6. Sieve Analysis of 3 g of Fibers from Reference Shaped Chips

Reference shaped chips:					Dry weight (3 g)	
Sieve. N°	IS Sieve	Particle Size (mm)	Weight Retained (g)	Percentage Retained (%)	Cumulative Retention (%)	Percentage Passing (%)
1	2 mm	2000	1.54	51%	51%	49%
2	1.4 mm	1400	0.46	15%	66%	34%
3	1 mm	1000	0.23	8%	74%	26%
4	800 µm	800	0.09	3%	77%	23%
5	600 µm	600	0.26	9%	86%	14%
6	400 µm	400	0.17	6%	92%	8%
7	200 µm	200	0.18	6%	98%	2%
8	Pan	0	0.07	2%	100%	0%
			3.00	100%		

Table 7. Sieve Analysis of 3 g of Fibers from Pre-treated Shaped Chips

Smashed shaped chips:					Dry weight (3 g)	
Sieve. N°	IS Sieve	Particle Size (mm)	Weight Retained (g)	Percentage Retained (%)	Cumulative retention (%)	Percentage passing (%)
1	2 mm	2000	1.40	47%	47%	53%
2	1.4 mm	1400	0.19	6%	53%	47%
3	1 mm	1000	0.30	10%	63%	37%
4	800 µm	800	0.08	3%	66%	34%
5	600 µm	600	0.21	7%	73%	27%
6	400 µm	400	0.27	9%	82%	18%
7	200 µm	200	0.34	11%	93%	7%
8	Pan	0	0.21	7%	100%	0%
			3.00	100%		

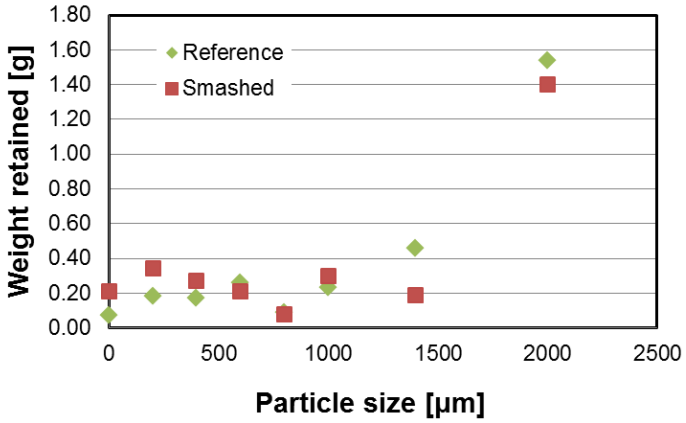

Fig. 8. Sieve results from 3 g of fibers from reference and pre-treated shaped chips; (his figure corresponds to the values shown in Table 6 and 7)

In summary, the results showed great potential to reduce energy consumption in fiber production by using dynamic compression as a pre-treatment before refining. However, it was not possible to fully analyze the properties of the fibers obtained, due to the large size of the resultant fibers and fiber bundles. This opens the door to a comparative analysis of the fiber quality from pre-treated and reference refined chips.

CONCLUSIONS

1. The results illustrate how dynamic compression exerted on a chip can damage the integrity of its structure, in the form of micro- and macro-cracks, resulting in a reduced energy demand during the subsequent refining processes. By using shaped wood chips with a specific degree of year ring orientation (45º) and treating them with a special device consisting of a free-falling cylinder with a fixed potential energy (54 J/g) at 20 °C, the overall energy consumption during the refining was reduced by

up to 48% compared with that of untreated chips (a 25% reduction if the energy costs of the pre-treatment are considered).

2. Cracks and particle size (or a combination of both) are suggested as the two main factors attributable to the energy reduction: i) cracks represent the beginning of the defibration process, hence reducing the amount of energy required during the refining process, and ii) the smashing effect reduces the consistency of the chips, which can be consequently broken up during the feeding process, also reducing the energy demands during refining by reducing their size. To this end, there is another side effect which is likely to the main factor attributable to the energy reduction. During the refining process of treated chips, peaks of energy are reduced, meaning that the energy reduction maintains a soft transition within the refining process. The variation in power is much reduced refining pre-treated than reference chips.
3. The level of energy reduction achieved here was higher than that previously reported in the scientific literature for TMP, suggesting that treatments for fiberboard pulp are more efficient than those for paper production, as the fibers require less work and less refining.
4. Micro- and macro-cracks appeared in random distribution across the surface, even sometimes completely breaking the sample into two or more pieces.
5. It was not possible to measure fiberboard pulp properties with conventional TMP equipment; therefore, an alternative method was used. It was determined that pre-treated fibers were softer, with lower water uptake and a higher fines content.
6. The method described here could represent a suitable alternative for increasing chip impregnability for chemical pulping.
7. Collimated chipping is a specific cutting process with a specific processing angle, facilitating the apparition of cracks. The smashing effect, on the other hand, uses the distribution of high energy over the whole chip structure, compressing the structure up to breakage. Thus, these two processes are fundamentally different, whereby collimated chipping is a machining type process, while the smashing tower is based on a dynamic compression device, able to exert large strikes of energy between two undeformable surfaces.

ACKNOWLEDGMENTS

Financial support for this work was provided within the framework of the PhD School DokIn´Holz funded by the Austrian Federal Ministry of Science, Research, and Economy and by the companies Fritz Egger GmbH, Doka Österreich GmbH, and Springer Maschinenfabrik AG. The authors thank Mr. Gerhard Emsenhuber, who assisted during the refining experiments.

REFERENCES CITED

Atack, D., Stationwala, M. I., and Karnis, A. (1994). "What happens in refining," *Pulp and Paper Canada* 85(12), 119-124.

Benthien, J. T., Hasener, J., Pieper, O., Tackmann, O., Bähnisch, C., Heldner, S., and Ohlmeyer, M. (2013). "Determination of MDF fibre size distribution: Requirements and innovative solution," in: *International Wood Composites Symposium*, Seattle, WA.

Bergander, A., and Salmén, L. (1997). "Lamellar cracks, Do they appear during radial compression of wood?" *Nordic Pulp and Paper Research Journal* 12(4), 216-21.

Björkqvist, T., Engberg, B. A., Salminen, L. I., and Salmi, A. (2012). "Towards optimal defibration: Energy reduction by fatiguing pre-treatment," *Nordic Pulp and Paper Research Journal* 27(2), 168-172.

Brill, J. (1985): Effects of wood and chip quality on TMP properties, 1985 *International Mechanical Pulping Conference, proceedings, SPCI Stockholm*, 153-161.

De Magistris, F., and Salmén, L. (2005). "Deformation of wet wood under combined shear and compression," *Wood Science and Technology* 39(6), 460-471.

De Magistris, F., and Salmén, L. (2006). "Mechanical behaviour of wet wood in sequences of compression and combined compression and shear," *Nordic Pulp and Paper Research Journal* 21(2), 231-236.

DIN 66165-2:2016-08 (2016). "Partikelgrößenanalyse - Siebanalyse - Teil 2: Durchführung," (Particle size analysis - Sieving analysis - Part 2: Procedure).

EN310 (1993). "Wood-based panels: Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels, Belgium.

EN317 (1993). "Particleboards and fibreboards – Determination of swelling in thickness after immersion in water," European Committee for Standardization, Brussels, Belgium.

EN319 (1993). "Particleboards and fibreboards – Determination of tensile strength perpendicular to the plane of the board," European Committee for Standardization, Brussels, Belgium.

Gerhards, C. C. (1982). "Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects," *Wood and Fiber* 14(1), 4-36.

Gorski, D., Hill, J., Engstrand, P., and Johansson, L. (2010). "Review: Reduction of energy consumption in TMP refining through mechanical pre-treatment of wood chips," *Nordic Pulp and Paper Research Journal* 25(2), 156-161.

Hellström, L. M., Carlberg, T., Engstrand, P., Gradin, P. A. and Gregersen, Ø. W. (2012). "Evaluation of collimated chipping technology for reducing energy consumption in mechanical pulping," *Journal of Science & Technology for Forest Products and Processes* 2(3).

Htun, M., and Salmén, L. (1996). "The importance of understanding the physical and chemical properties of wood to achieve energy efficiency in mechanical pulping," *Wochenbl. Papierfabrik* 124, 232-235.

Huang, F., Lanouette, R., and Law, K. N. (2012). "Morphological changes of jack pine latewood and earlywood fibers in thermomechanical pulping," *BioResources* 7(2),

1697-1712.
Itoh, S., Nagano, S., Fujita, M., and Takano, T. (1998). "Underwater shock wave loading on wood," *American Society of Mechanical Engineers, Pressure Vessels and Piping Division* 377, 231-234.
Kalpakjian, S., and Schmid, S. (2010). *Manufacturing Engineering and Technology*, Pearson, Jurong, Singapore.
Nelsson, E., Sanberg, C., Hildén, L., and Daniel, G. (2012). "Pressurized compressive chip pre-treatment of Norway spruce with a mill scale Impressafiner," *Nordic Pulp and Paper Research Journal* 27(1), 56-62.
Píriz, R. (2015). Personal communication.
Sabourin, M. (1998). "Optimizing thermomechanical pulping of Southern pine species using a compression pre-treatment," in: *TAPPSA African Pulp and Paper Week Conference*, Durban, South Africa, pp. 341-352.
Salmén, L. (2014). Personal communication.
Salmén, L., Tigerstrom, A., and Fellers, C. (1985). "Fatigue of wood – Characterization of mechanical defibration," *Journal of Pulp and Paper Science* 11(3), 68-73.
Uhmeier, A., and Salmén, L. (1996). "Repeated large radial compression of heated spruce," *Nordic Pulp and Paper Research Journal* 11(3), 171-176.
Viforr, S., and Salmén, L. (2005). "From wood shavings to mechanical pulp - A new raw material?" *Nordic Pulp and Paper Research Journal* 20(4), 418-422.
Viforr, S., and Salmén, L. (2007a). "Shear/compression treatment of wood material – A way of reducing energy demand in TMP processes," in: *International Mechanical Pulping Conference*, Minneapolis, MN, USA, pp. 1038-1044.
Viforr, S., and Salmén, L. (2007b). "Optimal shear/compression forces - A way of collapsing coarse TMP fibres," *Journal of Pulp and Paper Science* 33(1), 22-28.
Walker, J. C. F. (1993). *Primary Wood Processing: Principles and Practice*, Chapman & Hall, London, England.

Article submitted: June 7, 2017; Peer review completed: July 22, 2017; Revised version received and accepted: August 4, 2017; Published: August 22, 2017.
DOI: 10.15376/biores.12.4.7376-7394