Eur. J. Wood Prod. (2017) 75:215–232
DOI 10.1007/s00107-016-1094-2

ORIGINAL

Investigation of the interrelations between defibration conditions, fiber size and medium-density fiberboard (MDF) properties

Jan T. Benthien[1] · Sabrina Heldner[1] · Martin Ohlmeyer[1]

Received: 25 July 2015 / Published online: 1 August 2016

Abstract Defibration conditions and raw material properties affect wood fiber characteristics, and thereby the properties of fiber-based panels such as high-density fiberboard (HDF), medium-density fiberboard (MDF) and wood fiber insulation board. This study investigates the influence of steaming conditions (time and temperature), grinding disc distance, wood species (pine, beech, birch and poplar), method of refiner discharging (radial and tangential stock outlet) and wood chip size on fiber length and fiber length distribution, and further the influence of fiber size on MDF properties. Fiber lengths were determined applying the recently developed image analysis-based fiber size measuring system FibreCube. This system enables an automated and nearly complete mechanical separation of woolly-felted fiber samples prior to image acquisition, software-supported post-separation of overlapped-lying fibers at the beginning of image analysis, and flow line tracing-based length measurement. It was found that grinding disc distance and wood species are the most influential parameters on fiber length characteristics. Especially the content of undefibrated fiber bundles (shives) was found to strongly correlate with the grinding disc distance. Wood anatomical differences between hardwood and softwood were reflected clearly by the fiber length characteristics. Fiber size was found to be one of the parameters influencing panel properties. However, other fiber characteristics—in particular the chemical nature of the fiber, which is responsible for its wettability with water (thickness swelling) and glue (mechanical properties)—have to be considered as important influencing parameters on panel properties.

✉ Jan T. Benthien
jan.benthien@thuenen.de

[1] Thünen Institute of Wood Research, Leuschnerstraße 91c, 21031 Hamburg, Germany

1 Introduction

With a share of 23 % (11.7 mio m^3) of the European wood-based panel production (51.1 mio m^3) in 2010 (excluding Russia and Turkey), medium-density fiberbord (MDF) is the second most important wood-based panel after particleboard (Döry 2012). The worldwide production of MDF was 70 mio m^3 in 2010 (FAO 2010).

The main feedstock for MDF manufacturing—thermo mechanical pulp (TMP)—is usually obtained from a defibration process. After softening the wood matrix substance lignin in a digester, wood chips or sawmill residues (sawdust) are milled into fibers by the grinding discs of a refiner. With an increased degree of breakdown of the natural structure of wood, and, in consequence, a simultaneously increased degree of energy consumption (e.g., refiner engine power which again corresponds to the grinding disc distance), wood-based panels made of this raw material become more homogenous and isotropic, while strength properties decrease (Wagenführ et al. 2008). Steaming temperature, respectively wood chip temperature after steaming, determines how the natural wood structure is processed into fibers. At temperatures below lignin softening, the fibers are pulled out of the wood structure and consequently damaged, while at temperatures above lignin softening, the wood substance is separated into single fibers at the middle lamella (Wessbladh and Mohr 1999). Accordingly, the parameters of the defibration process determine the fiber quality achieved (Deppe and Ernst 1996).

Besides hot pressing and the amount and type of resin used, fiber quality (fiber size and morphology, surface characteristics, chemical properties, mechanical behaviors) is the most important variable affecting the manufacturing process and panel properties. For instance, fine-grained TMP is used to meet profiling requirements (deep router grade MDF), while coarser soft wood fibers are required to realize a low bulk density after mat forming in order to manufacture wood fiber insulation board. Aiming to manufacture thin MDF for direct lacquering or furniture-grade MDF, a low shive-content TMP is required in order to achieve a homogeneous panel surface.

Irrespective of the importance of fiber size-based characteristics for fiberboard production, manual fiber inspection has been performed for evaluation for a long time (Wessbladh and Mohr 1999) because no adequate measuring system was available on the market (Benthien et al. 2013). Today, shive control can reliably be conducted with the mat surface inspection system FiberView (Fagus-GreCon Greten GmbH & Co. KG (Grecon), Alfeld, Germany) as shown by its increasing application in the MDF industry (Hasener 2013a, b). Its high measuring frequency and automated feedback to the press control station in the form of characteristic values—e.g., number of shives per mat area—allows a quick adjustment of the digester and refiner settings. However, the FiberView is focused on shive detection on the mat surface and does not provide information on the composition of the fiber size and fiber size distribution in total. A more detailed fiber analysis is required to optimize the defibration process in sum (raw material composition, steaming parameters and refiner settings)—in particular with a view to optimizing panel properties.

As no system for the size characterization of fiberboard TMP was available in the market, the Thünen Institute of Wood Research (Hamburg, Germany), Hamburg University (Hamburg, Germany)—in particular Department of Wood Science and The Cognitive Systems Laboratory (KOGS)—and GreCon commenced development of the image analysis-based fiber size measuring system FibreCube in 2009. The aim of the last of three research projects was to finalize and apply the system to the investigation of considerable interrelations between defibration conditions, fiber size and fiberboard properties (Benthien et al. 2014a).

The intention of this paper is to present the results of the laboratory investigations conducted in the framework of the above-mentioned research project. In this regard, different fiber types were produced and analyzed as well as fiberboard manufactured and properties of these panels determined. The fiber size, the raw material source and defibration conditions were varied as influencing parameters.

2 State of the art

2.1 Fiber size characterization

To be consistent with the change from the wet to dry MDF production process, also in raw material characterization, Jensen and Seltmann (1969) focused on the development of dry fiber fractionation methods. In addition to the well-known sieve sorting technique in particleboard production, a vertical air stream classifier and the use of an air-jet sieve for fiber characterization were proposed. However, conventional sieve analysis has recently appeared to be unsuitable because fibers tend to agglomerate (formation of felted fiber balls) during sieving (Plinke et al. 2012). Air-jet sieving was found to be inadequate to determine the dust content (Wenderdel et al. 2014) and consequently inadequate for fiber analysis.

In the early stages of electronic data processing, Quirk (1981), Micko et al. (1982) and Myers (1983) began measuring fiber sizes with a handheld cursor on the basis of dry-scattered, optically magnified and projected fibers by tracing the fiber image from end to end. An in principal similar test setup, however with a digital camera for fiber imaging and a software-supported technique to trace each individual fiber manually, has been described by Lu et al. (2007). Although this approach is time-consuming and ineffective with regard to the amount of measured fibers, this procedure is still performed in practice. Nonetheless, the principles of this procedure form the basis of modern image analysis-based particle and fiber size measuring systems, while size measurement of the imaged fibers is arranged by automated software routines.

As is the case for sieving methods from the particleboard industry, measuring systems from the pulp and paper industry—based on aqueous fiber suspensions—seem to be inapplicable for the characterization of MDF fibers, too. This applies, in particular, to unadjusted image analysis-based fiber size measuring systems (as will be discussed below) and to wet sieve fractionation systems like the Bauer McNett (Frank-PTI GmbH, Birkenau, Germany) and the Master Screen/Shive-Analyser (Pulmac Inc.; Pointe-Claire, Canada). In the case of the two wet sieving techniques, undifferentiated information regarding fiber length and width is obtained, similar to wood particle sieve fractionation. Experiments from Roffael et al. (1994a) applying the image analysis-based measuring system Kajaani FS 200 (Metso Automation INC, Helsinki, Finland) showed that coarse fibers and fiber bundles tend to block the flow-cell. Funk (2013) conducted promising experiments applying the measuring system PulpVision (Andritz AG, Graz, Austria) from the pulp and paper industry, but with adjusted flow-cell for MDF fiber

measurement. Experiments conducted by Weber et al. (2014) using a combination of the QualScaṅs (Pulmac) dissolver unit and a Camsizer (Retsch GmbH, Haan, Germany) as photo unit showed again that MDF fibers tend to cause flow-cell blockages.

The major limitation of measuring systems with dry fiber preparation is to attain an adequate fiber separation prior to imaging. Basically, promising systems like the Camsizer and the QIC-PIC (Sympatec GmbH, Clausthal-Zellerfeld, Germany) are optimized on free-flowing particles but are unfortunately unable to separate fibers passing through a vibrating feeder channel. This applies as well when the vibrating feeder channel is combined with a dry air-flow disintegrator as in the case of the QIC-PIC. Sample preparation (manual disintegration of fiber lumps) in the case of the FibreShape (Innovative Sintering Technologies Ltd., Vilters, Switzerland) is laborious and time-consuming and surpasses microscopic measurements only by computer-assisted image analysis, as can be seen from a first attempt to apply FibreShape to fiber size measurement by Ohlmeyer et al. (2006). Attempts to solve limitations of these systems have not yet brought a breakthrough. Schmid (2013) proposed disintegrating fiber lumps with liquid solvents by placing the solution on a glass plate, evaporating the solvent and finally characterizing the fibers with the FibreShape system. This procedure may be useful for specific problems but will not help to speed up the measuring technique. Sympatec developed the so-called separation unit "Fibros", which aims to separate fibers with a brush head rotating on an air jet sieve prior to image capture. However, experiments by Benthien et al. (2014b) showed that fiber bundles remain in the brush and cannot be measured.

Weber et al. (2014) reported on a promising newly developed pneumatic short fiber rotation disperser, which separates dry fibers with different compressed air nozzles. While this system was successfully tested for wood flour within an industrial trial, MDF fiber analysis was subjected to various restrictions during first laboratory experiments.

Subsequent to adequate fiber separation prior to imaging, software-supported post-separation of overlapped-lying fibers at the beginning of image analysis is a further requirement. This serves to avoid incorrect fiber size measurements due to the interpretation of fiber agglomerates as undefibrated fiber bundles or the systematic exclusion of defibrated but just agglomerated (touching) fibers on the image. Since adequate fiber separation is one of the major challenges in image-based fiber characterization, in practice the number of excluded particles is quite high. Up to now, only few tools are known for post-separating fibers. One is offered as a feature for the glass fiber measuring system FASEP (xyz high precision, Darmstadt, Germany), a second—FiVer—was introduced by Popp (2013), applicable to straight shaped glass fibers without any curvature. The post-separation approach utilized from the FibreCube system has recently been introduced by Seppke et al. (2015).

Following mechanical fiber separation, image acquisition and, if possible, software-supported fiber post-separation, image analysis is the last step of image analysis-based fiber size measurement which can potentially be more or less suitable for fiber measurement. In the case of fibrous particles, fiber-tracing models should be preferred while models like the minimum area bounding rectangle model or the Feret diameters should be reserved for the analysis of rod-shaped particles like wood chips or splinters.

Based on this situation, the present paper applies the recently introduced image-based analysis system FibreCube, which was found to fulfill the requirements for MDF fiber size determination (Ohlmeyer et al. 2014).

2.2 Interrelations between refining parameters, fiber characteristics and fiberboard properties

Investigations on the interrelations between refining parameters, fiber characteristics and fiberboard properties were undertaken within various studies. As refining parameters, steaming temperature, steaming time, grinding disc distance and raw material were primarily varied. In the case of fiber characteristics, morphological properties like fiber size and fiber size distribution (e.g., wet sieve fractionation, air-jet-sieve analysis, microscopic measurements and image analysis) or fiber surface furnish (e.g., surface roughness), chemical properties (e.g., pH-value) and mechanical properties (e.g., strength and stiffness of individual fiber) were usually varied. As board properties, bending properties, internal bond strength and moisture related properties (e.g., thickness swelling) were normally measured.

As early as at the beginning of the 1970s the influence of refining pressure and steaming time on the moisture-related properties of UF-bonded MDF were investigated by Kehr and Jensen (1971), Gran and Bystedt (1973) and Kehr (1977) as was reported by Krug (2010). It was found that the steaming temperature influences the panel properties to a greater extent than the steaming time.

Myers (1983) investigated the influence of refining intensity (grinding disc distance, type of grinding disc) on fiber characteristics (drainage rate, Bauer-McNett screen analysis, microscopic length measurement). It was found that the fiber length decreased with increasing refining intensity.

Roffael et al. (1994a, b, 1995) reported about the suitability of TMP and CTMP (chemo-thermo-mechanical pulp) of beech and pine as a raw material for MDF

manufacture. Among other fiber characteristics, fiber length and the pH-value were determined for differently defibrated (variation of the digester temperature) wood chips. It was found for beech-TMP that an increase of steaming temperature led to decreased panel properties. This was explained by presumed lignin condensations on the fiber surface and consequently lowered glue accessibility.

Roffael et al. (2001) investigated the influence of pulping technique (TMP vs. CTMP) and pulping temperature on the fiber properties (e.g., pH-value, buffering capacity, pentosane content) and further the influence of pulping conditions and fiber properties on the MDF properties. It was found that the pentosane content decreases with increasing pulping temperature which was explained by the increased hemicellulose degradation. Lower pH-values were found for increased refining temperatures and were assumed to precure urea-formaldehyde resins during panel manufacture. Thickness swelling, water absorption and internal bond strength were found to improve with increasing pulping temperature. Similar findings have already been presented by Schneider and Roffael (2000). Schneider (1999) additionally mentioned decreasing bending strength with increasing refining temperature.

Roffael et al. (2009) investigated the effect of pulping temperature on the morphological properties of pine TMP. It was found that the fines content increased and fiber length and diameter decreased with increasing pulping temperatures.

Groom et al. (1997) investigated the effect of the individual wood fibers properties on the bending properties of MDF. It was found that the panels' stiffness and strength are inversely related to fiber stiffness and strength. Different micro fibril angles between juvenile and mature wood were assumed as explanation. Increasing panel properties at increasing refining levels (feed pressures of 10 and 40 psi) were explained by differences occurring in the surface morphology and consequently altered fiber-to-fiber stress transfer mechanism.

Groom et al. (1999) investigated the effect of fiber orientation, fines loading (varying portions of sieve fractions) and refining levels (feed pressures of 4, 8 and 12 bar) on the structural performance of MDF. It was again concluded that the different micro fibril angles of juvenile (45°) and mature wood (5–10°) are causal for the inverse relationship found between panel and individual fiber properties. The fact that the panel properties improved when oriented juvenile fibers served as raw materials for panel manufacture, was attributed to the higher micro fibril angle, thus higher fiber flexibility and consequently higher number of fiber-to-fiber contacts, which means stress can be transferred among the fibers. Increased fines contents were found to decrease the panel properties. This was explained by the lack of long fibers, resulting in low aspect ratios and ultimately poor physical interlocking and fiber-to-fiber contact.

Groom et al. (2000) investigated the effects of varying refiner pressure on the appearance of the fiber surface, chemical fiber composition, surface energy and mechanical fiber properties of TMP fibers. With increasing refiner pressure the hemicellulose content was found to decrease, the fiber surface to become torn and irregular (increased fiber surface roughness) and mechanical properties of especially juvenile fibers decreased. Mechanical MDF properties were found to be best in the range of 8–12 bar refining pressure, which was explained by low structural damages due to lignin softening in case of bending properties, and the better accessibility of the fibeŕs cellulose network. The number of intimate fiber-to-fiber contacts in case of internal bond strength was thus increased. Fiber roughness was found to be most closely related to MDF properties.

Findings from previous research on the influence of refining pressure on MDF properties (Groom et al. 1999, 2000) were validated by Groom et al. (2001). The additionally investigated influence of resin molecular weight on panel properties was found to be of minor relevance.

Groom et al. (2002) investigated the relationships between wood quality, refiner pressure and resin distribution and their influence on MDF panel properties. It was concluded from the findings that the refining pressure is the most important variable influencing the stiffness and strength of MDF. However, the conclusions drawn have to be treated with caution, since the refiner feed screw settings (throughput) and energy consumption were maintained at a constant level which means as a consequence grinding disc distance variation.

Shi et al. (2006) used multivariate modeling to study the MDF properties in relation to fiber characteristics. Fiber morphology was investigated with a HiRes Fiber Quality Analyzer (FQA) (OpTest, Hawkesburg, Canada) and a Bauer-McNett classifier. Although, for example the arithmetic mean fiber length, the arithmetic fine fiber percentage or pH-value, were found to significantly affect various panel properties, the presence of dummy variables in the model suggests that fiber characteristics, other than those measured in that study, had significant effects.

Xing et al. (2006) investigated the effect of retention time of preheating and steam pressure of thermo-mechanical refining process on the MDF properties. Both were found to affect panel properties, but at varying degrees with regard to the investigated property.

Xing et al. (2008) investigated the effect of refining pressure on fiber properties by nanoindentation and atomic force microscopy. It was found that the size of cracks in the

cell wall (no cracks, nano-cracks, micro-cracks) increased with increasing refining pressure. With increasing refining pressure, nano-mechanical fiber properties were found to decrease in the case of the elastic modulus and hardness and increased in the case of creepage. Nanoindentation experiments were more precisely described by Xing et al. (2009).

Ohlmeyer et al. (2006) characterized the morphology (fiber length and width) of TMP with FibreShape. It was found that fibers from different manufacturers could be clearly distinguished from each other.

Lu et al. (2007) measured the length of fibers from different sources by microscopy analysis.

Wenderdel and Krug (2012) used air-jet-sieve analysis to investigate the influence of pulping pressure and grinding disc distance on the morphological characteristics of TMP. It was found that the fines and distribution of the fiber cross-sections are independent from the pulping pressure.

Wenderdel et al. (2013) investigated the influence of defibration temperature caused fiber surface roughness on MDF properties and proved the assumption of a previous publication by Wenderdel and Krug (2012) that not fiber size is causal for worsened panel properties at increased pulping pressure, but rather more likely the interrelation between fiber and resin (fiber surface characteristic) is hampered.

Ibrahim et al. (2013) investigated the effect of refining pressure and preheating time on MDF properties from oil palm trunk. Best panel properties were found at refining conditions of 6 bar refining pressure and 300 s preheating time.

Benthien et al. (2014c) investigated the influence of fiber size distribution on MDF properties caused by varied steaming time and temperature. It was shown that all measured property values increased with increasing fiber length.

Sliseris et al. (2016) introduced two methods for estimating the fiber orientation and fiber bundles in MDF as fiber orientation and fiber bundles are assumed to significantly affect the strength and stiffness of fiberboards.

Although a variety of aspects were investigated in the above-mentioned studies, in summary no comprehensive picture can be drawn as each investigation has its weaknesses. One of the main problems is that defibration conditions are not comparable with each other. This is because different machines or machinery settings are applied and also due to unintended variations of, for example, the grinding disc distance. Within an introductory literature review on the influence of defibration conditions on the morphological characteristics of pine wood fibers, Wenderdel and Krug (2012) hypothesized changes in the grinding disc distance to be a side effect of defibration pressure. Further on, the applied techniques for fiber characteristic-measurement were inadequate (e.g., sieve analysis for fiber size measurement as discussed in the previous chapter) or the range of measured characteristics was insufficiently comprehensive. The present study will not solve this problem, as it focuses on the accuracy of fiber length measurement. However, it provides a partial contribution to the understanding of the complex interrelations of fiber manufacture, fiber characteristics and fiberboard properties.

3 Materials and methods

3.1 Materials

Scots pine (*Pinus sylvestris*), beech (*Fagus sylvatica*), birch (*Betula* spp.), poplar (*Populus* spp.) and a mixture of pine and beech (50/50 wt) were chipped and afterwards defibrated using a laboratory thermo-mechanical refining process at the Institut für Holztechnologie Dresden gGmbH (IHD), Dresden, Germany.

Liquid urea–formaldehyde (UF) resin (Kaurit 350, BASF, Ludwigshafen, Germany) was used as an adhesive in the manufacture of experimental MDF panels. Ammonium nitrate (NH_4NO_3) solution with 40 % solid content was used as a hardener for the UF resin.

3.2 Wood chip size characterization

Wood chip size distribution was determined in accordance with a characterization method which was initiated by the Haindl Papier GmbH & Co. KG (Augsburg, Germany), taken over by UPM-Kymmene Corporation (Helsinki, Finland) in 2001. This so called Haindl-method has a high degree of similarity to the test procedure of SCAN-CM 40:01. Deviations from this standard (SCAN-CM 40:01) are due to the fact that the investigator has to characterize by-products exclusively from sawmills as raw materials for pulp and paper manufacturing and the classification with slots instead of holes provided more useful results with a high significance on the final product.

For wood chip size distribution a portion of about 10 liter of air-dried wood chips was used. Deviations between the applied test details and the standard specifications (SCAN-CM 40:01) were: Tray 3 was performed as a 4 mm slot instead of a 13 mm hole, Tray 4 as a 2 mm slot instead of a 7 mm hole and Tray 5 as a 5 mm hole instead of a 3 mm hole. Shaking time (10 min), stroke (120 mm) and frequency (160 cycles per min) were in accordance with SCAN-CM 40:01. Prior to testing, the wood chips were spread to dry at ambient conditions.

3.3 Fiber manufacturing

With the intention of manufacturing TMP of different qualities, the defibration parameters as well as the wood species used were varied. Due to different availability, chipping and defibration were arranged in two series. Within the first test series (Chipping series A), pine and beech fibers were manufactured in order to investigate the influence of steaming temperature and time as well as the influence of stock outlet on fiber size. The variation of wood species and grinding disc distance (GDD) were arranged within Chipping series B. This procedure required the manufacture of a reference fiber (wood species: pine, steaming temperature: 170 °C, steaming time: 4 min, GDD: 0.15 mm, stock outlet: radial) for each chipping, respectively, defibration series. As a positive side effect, the influence of a newly adjusted chipping, respectively, defibration process can be studied at similar target settings.

In order to determine the influence of steaming time and steaming temperature on the fiber size, five combinations of differently defibrated fibers (a–e) were compiled:

(a) GDD (0.15 mm), stock outlet (radial) and wood species (pine) constant; steaming temperature and time were varied simultaneously (200 °C, 8 min; 170 °C, 4 min; 143 °C, 1 min);
(b) steaming temperature (170 °C), GDD (0.15 mm), stock outlet (radial) and wood species (pine) constant; steaming time were varied (1, 4, 8 min);
(c) steaming temperature (200 °C), GDD (0.15 mm), stock outlet (radial) and wood species (pine) constant; steaming time were varied (4, 8 min);
(d) steaming time (4 min), GDD (0.15 mm), stock outlet (radial) and wood species (pine) constant; steaming temperature were varied (170, 200 °C);
(e) steaming time (4 min), GDD (0.15 mm), stock outlet (radial) and wood species (beech) constant; steaming temperature were varied (164, 170 °C).

The influence of stock outlet (radial, tangential) was determined on fibers where steaming temperature (170 °C), steaming time (4 min), wood species (pine) and GDD (0.15 mm) were kept constant. The influence of GDD (0.06, 0.15, 0.6 mm) was determined on fibers where steaming temperature (170 °C), steaming time (4 min), stock outlet (radial) and wood species (pine) were kept constant. The influence of wood species (pine, beech, birch, poplar and a mixture of pine and beech) was determined on fibers where steaming temperature (170 °C), steaming time (4 min), GDD (0.15 mm) and stock outlet (radial) were kept constant. Subsequent to the refining process the fibers were dried by a flash tube dryer (blow-line) and collected in plastic bags. Table 1 lists name, chipping series and manufacturing details of the investigated fibers.

3.4 Fiber size characterization

Fiber lengths were determined applying the image analysis-based fiber size measuring system FibreCube which

Table 1 List of name, chipping series and manufacturing details (wood species, steaming time and temperature, grinding disc distance and stock outlet) of the investigated fibers

Fiber name	Chipping series	Wood species	Steaming temperature (°C)	Steaming time (min)	Grinding gap distance (mm)	Stock outlet
A1	A	Pine	143	1	0.15	Radial
A2	A	Pine	170	4	0.15	Radial
A3	A	Pine	200	8	0.15	Radial
A4	A	Pine	170	1	0.15	Radial
A5	A	Pine	170	8	0.15	Radial
A6	A	Pine	200	4	0.15	Radial
A7	A	Beech	164	4	0.15	Radial
A8	A	Beech	170	4	0.15	Radial
A9	A	Pine	170	4	0.20	Tangential
B1	B	Pine	170	4	0.06	Radial
B2	B	Pine	170	4	0.15	Radial
B3	B	Pine	170	4	0.6	Radial
B4	B	Beech	170	4	0.15	Radial
B5	B	Pine/beech	170	4	0.15	Radial
B6	B	Birch	170	4	0.15	Radial
B7	B	Poplar	170	4	0.15	Radial

was developed by the Thünen Institute of Wood Research, Department of Wood Science, KOGS, and Grecon during the past years. According to Benthien et al. (2014c), the FibreCube can be classified as a dry fiber image analysis-based system: fiber separation is arranged in an air-borne state and image acquisition is done as soon as the fibers are placed onto a glass plate. Subsequent to image recording, the length, width and intensity (grey scale value) of each captured fiber was determined by a fiber flow line tracing-algorithm. Detailed descriptions of the soft- and hardware design of this fully automatic operating measuring system can be found in previous publications (Benthien et al.2013, Benthien et al. 2014c; Ohlmeyer et al. 2014, 2015a, b; Seppke et al. 2015).

During fiber size measurement, approximately 530 images are captured within one run of three replicate measurements and analyzed. The result of each image analysis is a table of fiber statistics, which is exported to a CSV-file for further analysis by means of MatLab (MathWorks, Natick, Massachusetts, USA).

Within a first data processing step, MatLab extracts all information necessary for the determination of fiber length and fiber length distribution from the CSV-files and generates a mat-file. This step paves the way for a quick data treatment and result output afterwards. The characteristic values used for fiber characterization in this study are based on:

- the number of detected fibers and the initial sample weight,
- the fiber length and
- the smoothed double length-weighted frequency distribution.

3.4.1 Normalized number of fiber

The normalized number of fibers is defined as the quotient of the number of fibers and the initial sample weight in mg. This value does not correspond to the real number of fibers per sample weight, because only a small part of the separated fibers is photographed and detected by the software. Consequently, the normalized number of fibers can be used as a characteristic value describing the fineness, but the fibers are not counted quantitatively.

3.4.2 Double length-weighted fiber length

The double length-weighted fiber length is calculated in accordance with ISO 22314 by dividing the sum of the cubed fiber length (l^3) by the sum of the squared fiber length (l^2). In comparison to the mean (un-weighted) fiber length, this characteristic value is much more useful, because small dust particles are taken out of the focus by over-representing the more significant fibrous objects (weighting principle).

3.4.3 Double length-weighted relative frequency distribution

The double length-weighted relative frequency distribution is displayed in the form of five characteristic values (0–0.3, 0.3–1, 1–3, 3–6, >6 mm), indicating the composition (dust, fines, fibers, coarse particles and fiber bundles) of the fiber sample, and graphical plot. For this, each detected and length-measured fiber is assigned to one of 656 length classes (width of each class is 0.05 mm). For each length class, the number of fibers and mean squared fiber length, and further on, the double length-weighted frequency is calculated. Fitted on this data set, a polygonal function equation is set up smoothing the histogram and transferring the frequency distribution into a mathematically manageable description.

3.5 Fiberboard preparation and property determination

The fibers to be glued were arranged in a rotary drum blender equipped with an air-atomizing spray system. Prior to application, 1 % hardener (based on the resin solid content) and additional water was added to the resin solution. The amount of water was calculated in respect to fiber moisture content, so that 12 % target moisture content was reached after pressing. Resin content was 12 % based on dry fiber mass. Fibers were weighed according to target density and manually formed into mats on an aluminum caul plate using a 500 × 500 mm^2 forming box. A second such plate was laid on the top while both were covered with siliconized paper to prevent adherence between the panel and plates. After cold pre-pressing at a specific pressure of 16 N/cm^2 for approximately 2 min, the mats were transferred to a computer-controlled hot press, operated in plate position control mode. Hot pressing temperature, maximal specific pressure and press time factor were 190 °C, 716 N/cm^2 and 12 s/mm (192 s), respectively. Target panel thickness was 16 mm.

A total of 16 MDF test panel types were manufactured; three panels for each fiber type. The target density was 650 kg/m^3. Panels were allowed to cool and edges were trimmed prior to sample cutting. The number of test specimens for each panel type was 12 for modulus of elasticity (MOE) and modulus of rupture (MOR), and 18 for internal bond strength (IB), thickness swelling (TS), water absorption (WA) and surface soundness (SS). Test

specimens were conditioned in a climatic chamber at 20 °C and 65 % relative humidity (RH) for two weeks before testing.

MOE and MOR were determined according to EN 310 applying sample dimensions of 370 × 50 × 16 mm^3. IB tests were conducted according to EN 319 applying sample dimensions of 50 × 50 × 16 mm^3. By applying sample dimensions of 50 × 50 × 16 mm^3, TS and WA were determined after 2 and 24 h of immersion in water according to EN 317. With the same sample dimensions of 50 × 50 × 16 mm^3 SS were tested according to EN 311.

3.6 Statistical analysis

A single factor analysis of variance (ANOVA) and a Tukey HSD test were conducted using the analysis tool of SAS JMP in order to evaluate the significance of differences among fiber length and fiber length distribution and mean property values of MDF test panels. The null hypothesis (no effect) was accepted if the p value exceeded the $\alpha = 0.05$ significance level.

4 Results and discussion

4.1 Wood chip characterization

The homogeneity of wood chip heating and soaking in the digester is influenced by the wood chip size distribution. In the case of a narrow size distribution it can be assumed that the wood chips reached a consistent level of temperature and moisture penetration. Exceeding a certain level of temperature or exposure time, the wood substance (hemicelluloses) is degraded, while too low temperature and inconsistent moisture penetration inhibit the lignin softening. In consequence, defibration is incomplete and results in fibers with an increased amount of splinters and shives.

For Chipping series A, 1.7 kg pine and 2.6 kg beech were applied. In the case of Chipping series B 1.8 kg pine, 3.0 kg beech, 2.4 kg birch, 1.6 kg poplar and 2.0 kg of a pine/beech mixture were applied. Because wood chip volume and moisture were not measured, no information about the bulk density is available.

As can be seen in Table 2, a narrow size distribution was achieved for both Chipping series A and B.

Fifty or more percent of the wood chips were found on Tray number 3. The major part of the remaining chips was found on Trays number 2 and 4. The share of oversize chips (Tray number 1), pin chips (Tray number 5) and fines (final/bottom) can be neglected. The wood chip characterization indicates that differences in fibers result from varied defibration conditions, respectively wood species, and is not to be attributed to an insufficient chipping process. However, comparing fibers defibrated at nominally equal defibration conditions, but manufactured within different chipping and defibration series, differences have to be attributed to differences in wood chip size.

4.2 Influence of steaming time and temperature

Five groups (a–e) of fibers were formed to study the influence of steaming time and temperature on fiber size and further that of fiber size on panel properties:

(a) Influence of simultaneous increase of steaming time and temperature (A1, A2, A3).
(b) Influence of steaming time at a steaming temperature of 170 °C (A4, A2, A5).
(c) Influence of steaming time at a steaming temperature of 200 °C (A6, A3).
(d) Influence of steaming temperature at a steaming time of 4 min (pine) (A2, A6).
(e) Influence of steaming temperature at a steaming time of 4 min (beech) (A7, A8).

4.2.1 a: Influence of simultaneous increase of steaming time and temperature

For those fibers combined in Group a) optical fiber appearance and fiber size characteristics were found to indicate that the intensification of steaming conditions—from 143 °C, 1 min (A1) to 170 °C, 4 min (A2) and further to 200 °C, 8 min (A3)—causes a decrease of fiber size. The amount of fine fibers (0–0.3 mm) increases while the share of coarse particles (3–> 6 mm) decreases. With intensifying steaming conditions the mean fiber length was found to decrease while the normalized number of fibers increased. This finding fits well with findings by Roffael et al. (2009), who found a decreased fiber length and increasing fines content for pine wood TMP at increased steaming temperature from 140 to 180 °C. Decreased coarseness of fibers defibrated at higher temperatures can be explained by reaching, respectively exceeding the glass transition temperature of the lignin (approximately 170 °C for softwood and 155 °C for hardwood) which causes softening and consequently easier and more intense defibration of the wood substance. This effect can be understood by a paper from Asplund (1939) giving the electric energy consumption of hard- and softwood as a function of defibration temperature. Groom et al. (2000) and Groom et al. (2001) mentioned a physical breakdown (fragmentation) in fiber length at or above 10 bar pressure in the refiner.

In addition to coarseness, darkening of the fiber color was visually noticed under intensified steaming conditions. This indicates a modification of the chemical fiber structure

Table 2 Wood chip size distribution according to SCAN-CM 40:01, determined applying a portion of approximately 8–10 L air-dried wood chips each

Tray number	Fraction class	Screen specifications	Relative mass per fraction (%)						
			Chipping series A		Chipping series B				
			Pine	Beech	Pine	Beech	Pine/Beech mixture	Birch	Poplar
1	Oversize chips	45 mm hole	0.0	0.6	0.7	0.0	0.0	0.0	0.0
2	Overthick chips	8 mm slot	17.5	35.0	30.1	20.2	29.0	18.0	2.7
3	Large accept chips	4 mm slot	56.5	49.9	50.5	53.8	49.9	66.6	66.2
4	Small accept chips	2 mm slot	19.7	11.0	13.4	15.2	13.3	13.4	22.0
5	Pin chips	5 mm hole	4.0	2.5	4.0	7.5	4.8	1.6	7.4
Final	Fines	Tray	2.3	1.0	1.3	3.3	3.0	0.3	1.7

Deviations to standard specifications (Tray 3: 13 mm hole, Tray 4: 7 mm hole, Tray 5: 3 mm hole): Tray 3 was performed as 4 mm slot, Tray 4 as 2 mm slot and Tray 5 as 5 mm hole

(lignin condensation and hemicellulose degradation), as it is well known for wood as a result of heat treatment (Esteves and Pereira 2009). Groom's description (Groom et al. 2002) of the visual appearance (color and coarseness) of fibers defibrated at different refining temperatures coincides with the observation made for the fibers in this chapter. Schiegl (2004) explained the color change of the fibers with the oxidative split of lignin and the quicker darkening of those lignin fragments by their photochemical properties. Roffael et al. (2001) and Schneider et al. (2004) proved the increasing degradation of hemicelluloses at increased steaming temperature for fibers defibrated at intensified steaming conditions.

Aside from increased steaming temperature and time, the higher degree of defibration may be the result of unintended changes (reduction) of the grinding disc distance at intensified steaming conditions. Thermal expansion of machinery parts (grinding discs, drive shaft, etc.) at increased steaming temperatures may be the reason for that, as hypothesized by Wenderdel et al. (2012) in the framework of an introductory literature review on the influence of defibration conditions on the morphological characteristics of pine wood fibers.

With the exception of the MOR of test panels made of Fiber A1, all properties were found to increase with increasing fiber length (combined examination of Tables 3, 4). That means an improvement of mechanical properties and worsening of TS and WA. These findings correspond with results from Schneider (1999), who found improved bending strength and worsened TS and WA at decreased steaming temperature from 180 to 140 °C. Combining Schneider's findings with those of Roffael et al. (2009) mentioned before (increased fiber length at decreased steaming temperature), findings of the present study are confirmed. Groom et al. (2002) found as well increased bending properties for MDF made of long fibers. However, the highest mean fiber length was found for fibers refined at pressures between 6.3 and 8 bars (approximately 165 °C) investigating a range between 2 and 12 bars. Rofaell et al. (2001) investigated the influence of defibration temperature and steaming time on the chemical fiber properties (hemicellulose content, pH-value) and panel properties as IB, TS and WA. It can be concluded from given results that the degradation of hemicellulose at increased steaming temperature is responsible for the decrease of TS and WA due to the decrease of hydrophilic components in the wood fiber material. This fits well with the current findings on the evolution of TS and WA with increasing steaming intensity. Just as was found in this investigation, Rofaell et al. (2001) found decreased IB with intensified steaming conditions. Combining this finding with that of pH-value determination, not only the fiber size has to be assumed as an influencing parameter on the IB but rather more the decreasing pH-value at increasing steaming conditions which may lead to premature curing of the resin and consequently weakening of the bonding between the fibers. Schneider (1999) further claimed decreased pH-value to be responsible for simultaneous embrittling of the glue joints and consequent weakening of the strength properties. This does apply as well to TS, which was found to decrease with increasing steaming intensity in the present study. A further explanation for worsened mechanical panel properties and improved physical panel properties with intensified steaming conditions may be the decreased wettability of the fibers with glue due to the decreased amount of hemicellulose and consequently increased lignin content as mentioned by Roffael et al. (1995). The increased fiber surface due to the increasing number of fibers and consequently increased surface to be glued with the same amount of glue may also be a reason for mechanical property weakening. Improved

Table 3 Fiber size characteristics

		Fiber code	Number of repetitions (pcs)	Number of fibers per repetition (10^3 pcs)	Initial sample weight per repetition (g)	Normalized number of fibers (pcs/mg)	Double length-weighted fiber length (mm)	Double length-weighted relative frequency				
								0–0.3 mm (%)	0.3–1.0 mm (%)	1.0–3.0 mm (%)	3.0–6.0 mm (%)	>6.0 mm (%)
Influence of steaming temperature/time												
a)	143 °C/1 min	A1	10	159 (15)	0.51 (0.02)	313 (30) C	3.23 (0.10) A	1.9 (0.0) B	9.1 (0.5) C	45.8 (1.4) C	32.7 (1.0) A	10.5 (1.2) A
	170 °C/4 min	A2	10	222 (14)	0.49 (0.01)	456 (21) B	2.64 (0.08) B	2.2 (0.2) B	11.7 (0.8) B	54.5 (1.2) B	27.0 (1.4) B	4.7 (0.5) B
	200 °C/8 min	A3	10	265 (37)	0.51 (0.02)	514 (65) A	2.32 (0.07) C	3.3 (0.5) A	15.8 (1.0) A	56.5 (0.6) A	21.3 (1.1) C	3.1 (0.5) C
b)	170 °C/1 min	A4	3	178 (20)	0.50 (0.02)	357 (28) B	3.19 (0.10) A	1.9 (0.3) A	8.7 (0.4) A	46.0 (2.0) A	33.6 (1.1) A	9.8 (1.3) A
	170 °C/4 min	A2	10	222 (14)	0.49 (0.01)	456 (21) A	2.64 (0.08) B	2.2 (0.2) A	11.7 (0.8) B	54.5 (1.2) B	27.0 (1.4) B	4.7 (0.5) B
	170 °C/8 min	A5	3	170 (13)	0.50 (0.01)	340 (28) B	3.08 (0.11) A	1.8 (0.3) A	9.1 (0.4) A	48.2 (2.0) A	32.6 (0.8) A	8.3 (1.3) A
c)	200 °C/4 min	A6	3	248 (32)	0.54 (0.01)	463 (62) A	2.55 (0.13) A	2.0 (0.3) B	11.7 (1.2) B	57.2 (1.3) A	25.1 (1.6) A	3.9 (0.8) A
	200 °C/8 min	A3	10	265 (37)	0.51 (0.02)	514 (65) A	2.32 (0.07) B	3.3 (0.5) A	15.8 (1.0) A	56.5 (0.6) A	21.3 (1.1) B	3.1 (0.5) A
d)	170 °C/4 min	A2	10	222 (14)	0.49 (0.01)	456 (21) A	2.64 (0.08) A	2.2 (0.2) A	11.7 (0.8) A	54.5 (1.2) B	27.0 (1.4) A	4.7 (0.5) A
	200 °C/4 min	A6	3	248 (32)	0.54 (0.01)	463 (62) A	2.55 (0.13) A	2.0 (0.3) A	11.7 (1.2) A	57.2 (1.3) A	25.1 (1.6) A	3.9 (0.8) A
e)	164 °C/4 min (beech)	A7	3	150 (6)	0.53 (0.02)	283 (24) A	2.32 (0.24) A	7.0 (0.5) A	23.3 (2.1) A	43.2 (2.9) A	20.8 (2.3) A	5.7 (2.5) A
	170 °C/4 min (beech)	A8	3	183 (65)	0.52 (0.02)	347 (112) A	1.93 (0.17) A	5.7 (1.8) A	28.2 (4.8) A	47.6 (4.4) A	16.1 (1.8) B	2.4 (0.6) A
Influence of stock outlet												
Radial[a]		A2	10	222 (14)	0.49 (0.01)	456 (21) A	2.64 (0.08) B	2.2 (0.2) A	11.7 (0.8) A	54.5 (1.2) A	27.0 (1.4) B	4.7 (0.5) B
Tangential[b]		A9	3	185 (26)	0.51 (0.02)	366 (64) B	3.09 (0.06) A	1.8 (0.5) A	8.8 (0.5) B	47.7 (0.2) B	33.5 (1.0) A	8.3 (0.3) A
Influence of grinding gap distance (mm)												
0.06		B1	3	210 (15)	0.49 (0.01)	432 (31) A	2.64 (0.09) B	1.6 (0.1) A	10.8 (0.8) A	55.5 (1.8) A	28.0 (1.9) B	4.2 (0.7) B
0.15		B2	3	164 (13)	0.48 (0.02)	340 (34) B	3.02 (0.11) B	1.8 (0.2) A	9.1 (0.7) A	48.7 (0.4) B	33.3 (0.8) A	7.1 (1.1) B
0.6		B3	3	69 (16)	0.49 (0.03)	141 (25) C	4.06 (0.33) A	1.4 (0.1) A	5.8 (1.1) B	39.8 (3.1) C	34.7 (1.0) A	18.3 (3.4) A
Influence of wood specie												
Scots pine		B2	3	164 (13)	0.48 (0.02)	340 (34) B	3.02 (0.11) A	1.8 (0.2) D	9.1 (0.7) E	48.7 (0.4) AB	33.3 (0.8) A	7.1 (1.1) A
Beech		B4	3	239 (11)	0.49 (0.03)	493 (30) A	1.71 (0.01) D	7.1 (0.5) A	30.9 (0.6) A	47.7 (0.8) AB	13.1 (0.3) D	1.2 (0.1) C
Scots pine/beech[c]		B5	3	236 (30)	0.50 (0.03)	475 (38) A	2.54 (0.07) B	3.5 (0.4) C	16.2 (1.3) D	48.8 (0.2) A	27.0 (1.7) B	4.6 (0.3) B
Birch		B6	3	267 (8)	0.50 (0.03)	536 (15) A	2.45 (0.08) B	3.7 (0.2) C	22.5 (0.8) C	46.6 (1.4) BC	20.3 (0.3) C	7.0 (1.2) A
Poplar		B7	3	238 (10)	0.48 (0.01)	496 (8) A	2.21 (0.08) C	4.6 (0.1) B	26.9 (0.6) B	44.5 (0.6) C	18.8 (0.6) C	5.2 (0.7) AB
Influence of production time												
Chipping series A		A2	10	222 (14)	0.49 (0.01)	456 (21) A	2.64 (0.08) B	2.2 (0.2) A	11.7 (0.8) A	54.5 (1.2) A	27.0 (1.4) B	4.7 (0.5) B
Chipping series B		B2	3	164 (13)	0.48 (0.02)	340 (34) B	3.02 (0.11) A	1.8 (0.2) B	9.1 (0.7) B	48.7 (0.4) B	33.3 (0.8) A	7.1 (1.1) A

Groups with the same letter are not statistically different at a significance level of $\alpha = 0.05$

Displayed data: mean value (±standard deviation) homogeneous group; unless otherwise stated: wood species = Scots pine, steaming temperature = 170 °C, steaming time = 4 min, stock outlet = radial, grinding disc distance (GDD) = 0.15 mm

[a] GDD: 0.15 mm

[b] GDD: 0.2 mm

[c] Mixture of Scots pine and beech (50/50)

Table 4 Properties of the panels made of the investigated fibers

		Fiber code	Density (kg/m^3)	Internal bond strength (IB) (N/mm^2)	Thickness swelling (TS)		Water absorption (WA)		Bending modulus of		Surface soundness (SS) (N/mm^2)
					2 h (%)	24 h (%)	2 h (%)	24 h (%)	elasticity (MOE) (N/mm^2)	rupture (MOR) (N/mm^2)	
Influence of steaming temperature/time											
a)	143 °C/1 min	A1	678 (17)	0.90 (0.15) C	10.0 (2.5) C	17.1 (1.3) C	68.0 (9.1) B	89.4 (6.5) C	2834 (143) B	31.7 (1.4) B	1.70 (0.20) C
	170 °C/4 min	A2	677 (16)	0.72 (0.11) B	7.7 (2.5) B	16.2 (1.2) B	59.4 (9.6) AB	83.2 (6.7) B	2674 (122) AB	32.0 (1.9) B	1.55 (0.16) B
	200 °C/8 min	A3	687 (24)	0.37 (0.05) A	4.8 (1.7) A	7.7 (0.5) A	52.5 (16.5) A	68.3 (8.0) A	2573 (215) A	21.5 (2.0) A	1.31 (0.16) A
b)	170 °C/1 min	A4	666 (24)	0.81 (0.09) B	13.6 (0.7) C	18.0 (0.7) C	82.3 (8.0) C	93.8 (6.2) B	2473 (145) A	30.9 (2.0) B	1.65 (0.16) AB
	170 °C/4 min	A2	677 (16)	0.72 (0.11) A	7.7 (2.5) A	16.2 (1.2) B	59.4 (9.6) A	83.2 (6.7) A	2674 (122) B	32.0 (1.9) B	1.55 (0.16) A
	170 °C/8 min	A5	684 (23)	0.78 (0.05) AB	9.8 (1.1) B	14.7 (0.5) A	69.4 (8.9) B	84.5 (5.3) A	2604 (179) AB	28.9 (1.9) A	1.72 (0.12) B
c)	200 °C/4 min	A6	670 (25)	0.37 (0.15) A	5.4 (1.6) A	8.4 (0.6) B	57.4 (15.6) A	74.8 (10.1) B	2263 (148) B	20.7 (2.1) A	1.10 (0.28) A
	200 °C/8 min	A3	687 (24)	0.37 (0.05) A	4.8 (1.7) A	7.7 (0.5) A	52.5 (16.5) A	68.3 (8.0) A	2573 (215) A	21.5 (2.0) A	1.31 (0.16) B
d)	170 °C/4 min	A2	677 (16)	0.72 (0.11) B	7.7 (2.5) B	16.2 (1.2) B	59.4 (9.6) A	83.2 (6.7) B	2674 (122) B	32.0 (1.9) B	1.55 (0.16) B
	200 °C/4 min	A6	670 (25)	0.37 (0.15) A	5.4 (1.6) A	8.4 (0.6) A	57.4 (15.6) A	74.8 (10.1) A	2263 (148) A	20.7 (2.1) A	1.10 (0.28) A
e)	164 °C/4 min (beech)	A7	697 (25)	0.79 (0.12) A	14.0 (1.1) B	17.6 (1.3) B	73.6 (5.4) A	85.1 (5.4) A	2367 (268) A	23.6 (3.8) A	1.48 (0.32) A
	170 °C/4 min (beech)	A8	685 (16)	0.97 (0.08) B	12.4 (0.3) A	16.5 (0.3) A	74.1 (4.4) A	85.4 (3.7) A	2503 (188) A	26.1 (2.6) A	1.95 (0.27) B
Influence of stock outlet											
Radial[a]		A2	677 (16)	0.72 (0.11) B	7.7 (2.5) A	16.2 (1.2) A	59.4 (9.6) A	83.2 (6.7) A	2674 (122) B	32.0 (1.9) B	1.55 (0.16) B
Tangential[b]		A9	663 (22)	0.53 (0.13) A	10.4 (1.9) B	16.4 (1.5) A	73.0 (12.7) B	93.1 (6.8) B	2452 (179) A	28.7 (3.6) A	1.25 (0.28) A
Influence of grinding gap distance (mm)											
0.06		B1	653 (30)	0.55 (0.04) A	6.5 (2.5) B	15.6 (0.6) B	67.5 (15.6) B	96.1 (8.5) B	2591 (307) AB	28.9 (3.3) B	1.59 (0.14) A
0.15		B2	661 (22)	0.65 (0.08) B	2.6 (1.4) A	15.8 (0.3) B	45.8 (11.2) A	95.9 (6.7) B	2808 (227) B	31.7 (2.6) B	1.64 (0.16) A
0.6		B3	681 (30)	0.65 (0.07) B	8.6 (0.8) C	14.3 (0.3) A	69.8 (10.7) B	84.4 (7.1) A	2396 (304) A	24.1 (3.2) A	1.65 (0.19) A
Influence of wood specie											
Scots pine		B2	661 (22)	0.65 (0.08) C	2.6 (1.4) A	15.8 (0.3) B	45.8 (11.2) A	95.9 (6.7) C	2808 (227) B	31.7 (2.6) C	1.64 (0.16) C
Beech		B4	683 (26)	0.58 (0.04) B	10.7 (1.3) B	16.0 (0.3) B	66.7 (10.7) B	84.5 (6.8) AB	2636 (291) AB	27.1 (3.5) AB	1.63 (0.20) C
Scots pine/beech[c]		B5	675 (22)	0.55 (0.05) B	10.0 (1.0) B	15.9 (0.6) B	68.5 (8.5) B	86.2 (6.4) BC	2825 (273) B	28.8 (4.4) ABC	1.53 (0.18) BC
Birch		B6	665 (23)	0.44 (0.07) A	10.1 (3.5) B	19.4 (1.6) C	62.1 (17.5) B	89.5 (10.7) BC	2874 (341) B	29.4 (4.7) BC	1.40 (0.27) AB
Poplar		B7	659 (28)	0.39 (0.04) A	4.4 (2.4) A	13.0 (3.1) A	41.5 (15.4) A	75.1 (17.5) A	2456 (249) A	24.8 (2.5) AB	1.26 (0.13) A
Influence of production time											
Chipping series A		A2	677 (16)	0.72 (0.11) B	7.7 (2.5) B	16.2 (1.2) A	59.4 (9.6) B	83.2 (6.7) A	2674 (122) A	32.0 (1.9) A	1.55 (0.16) A
Chipping series B		B2	661 (22)	0.65 (0.08) A	2.6 (1.4) A	15.8 (0.3) A	45.8 (11.2) A	95.9 (6.7) B	2808 (227) A	31.7 (2.6) A	1.64 (0.16) A

Groups with the same letter are not statistically different at a significance level of $\alpha = 0.05$

Displayed data: mean value (±standard deviation) homogeneous group; IB, TS, WA, SS: n = 18; MOE, MOR: n = 12; unless otherwise stated: wood species = Scots pine, steaming temperature = 170 °C, steaming time = 4 min, stock outlet = radial, grinding disc distance (GDD) = 0.15 mm

[a] GDD: 0.15 mm

[b] GDD: 0.2 mm

[c] Mixture of Scots pine and beech (50/50)

bending properties at decreased steaming time and temperature may be explained by increased fiber length as loads in panel plane direction may thus be transferred more sufficiently.

4.2.2 b: Influence of steaming time at a steaming temperature of 170 °C

With the intention of determining the pure influence of steaming time on fiber size and further that of fiber size on panel properties, Fibers A4 (1 min), A2 (4 min) and A5 (8 min) were combined in a Group b). However, fiber length and fiber length distribution and panel properties were not as clearly graduated as could have been expected following the graduation of steaming time and the results obtained from Group a). Except for the dust content (0 to 0.3 mm), the characteristic values of the fibers steamed for 1 and 8 min were assigned to the same homogeneous group while the fibers steamed for 4 min were found to be significantly different. This result is hard to explain, because an extension of steaming time should (up to a certain degree) result in a more uniform heat penetration of the wood chips. In consequence, coarser particles have to be expected for lower steaming times and finer fibers for longer steaming times. Accordingly, differences between short time (A4: 1 min) and longer time steamed fibers (A2: 4 min; A5: 8 min) could have been expected.

Deviating from the intended aim, this trial demonstrates that the variation of defibration parameters (here steaming time) has to be changed carefully and stepwise successively. In the course of sample manufacture, fiber A4 (1 min) was produced first, followed by fiber A5 (8 min) and finally fiber A2 (4 min). Maybe the order of sample manufacture is the reason for the lack of fiber size and panel property graduation.

4.2.3 c: Influence of steaming time at a steaming temperature of 200 °C

In contrast to the experiment described earlier, the influence of steaming time on fiber size and further that of fiber size on panel properties can be understood at a steaming temperature of 200 °C, varying the steaming time from 4 min (A6) to 8 min (A3). Except for occasionally lacking significance, the increase of steaming time resulted in an increase of measured fibers per mg sample, decrease of fiber length, increase of short fibers and decrease of coarse fibers.

The reduction of TS and WA (both 24 h) can be well explained as for Group a) with an increased hydrophobic character of the fibers. The increase of surface soundness and MOE with increased steaming time indicates a denser surface layer, which may be the result of finer and presumably more easily compactable particles.

4.2.4 d: Influence of steaming temperature at a steaming time of 4 min (pine)

The influence of steaming temperature on fiber size and further that of fiber size on panel properties was investigated on Fiber A2 (170 °C) and A6 (200 °C), both steamed for 4 min regardless of lacking statistical significance, mean values of fiber size characteristics indicate that wood defibration intensifies with increased steaming temperature. Panel properties coincide as well with the findings of Group a): intensified defibration conditions (here steaming temperature only) result in decreased mechanical properties but improved TS and WA. Based on panel properties and the visual impression of the fibers, more differences in fiber characteristics would have been expected. However, due to the fact that color and non- morphological properties like stiffness are not covered by image-based fiber size analysis, lacking differences between fibers are understandable.

4.2.5 e: Influence of steaming temperature at a steaming time of 4 min (beech)

The results of this test set-up (beech, 4 min, 164 and 170 °C) reflect the results of Group d), while steaming temperature was at a lower level. As beech was applied instead of pine as raw material here, fiber sizes were found to be much smaller than for fibers from pine because of their wood anatomical differences.

The influence of steaming time were found as could be expected from the results of Group a): with intensified steaming conditions the number of fibers increased, the fiber length decreased, the frequency of short fibers increased and the frequency of coarse fibers decreased. This finding stands in opposition to Roffael et al. (1994a), who found shorter beech fibers when defibrated at 150 °C than those defibrated at 170 °C. Also in contrast to findings of the present research, Roffael et al. (1995) found panel properties decreased at increased steaming temperature.

4.3 Influence of stock outlet

The influence of stock outlet (radial vs. tangential) on the fiber size and further that of fiber size on panel properties was addressed by Fiber A2 (radial) and Fiber A9 (tangential). The results from fiber size analysis fit well with the results of Mäbert and Krug (2009) who investigated the influence of radial and tangential refiner discharging and found radially discharged fibers significantly finer than tangentially discharged fibers. However, knowing of the major influence of grinding disc distance on the fiber size (see next chapter) it is difficult to attribute the measured differences in fiber size to only the applied stock outlet (radial and tangential) because the grinding disc distance

was not able to stay consistent for both fibers. The nominal grinding disc distance was 0.15 mm in the case of radial discharging, and 0.2 mm for tangential discharging and surely overlaps the effect of stock outlet.

The nearly overall significantly superior properties of test panels made from radially discharged fibers are at the first moment not conclusive because tangential discharging was assessed to be more gentle and fiber-protecting by Mäbert and Krug (2009). However, higher fiber surface roughness for radially discharged fibers—as concluded by Mäbert and Krug (2009) on the basis of dewatering behaviors of differently discharged fibers—may be the reason for superior panel properties.

4.4 Influence of grinding disc distance

The influence of the grinding disc distance on the fiber size and further that of fiber size on panel properties were studied on Fibers B1 (0.06 mm), B2 (0.15 mm) and B3 (0.6 mm), manufactured at successively adapted grinding disc distances within defibration Series B. Except for the double length-weighted relative frequency of the fine fibers (0–3 mm) and occasionally lacking significance, a clear increase of fiber coarseness was found for increasing grinding disc distances (Table 3). This finding confirms the common experience from haptic and visual fiber characterization of industrial process optimization trying to keep refining energy as low as possible and at the same time the shive content below a maximum acceptable level.

The panel properties made of fibers B1, B2 and B3 do not follow a graduation that would be expected from fiber size distribution when anticipating improved properties with increasing fiber length. It seems like the middle of the chosen grinding disc distances (0.15 mm) is optimal in respect to panel properties, while fiber size cannot be set out as a reason for such an assumption. Maybe there is an optimal ratio of fines and fibers where the fines fill the voids between the fibers and thus provide a greater degree of bonding and, consequently, increasing strength properties as mentioned by Groom et al. (2002). Obviously, fiber size alone is not responsible for high mechanical properties. The grinding disc distance seems to be of more importance, aiming at low shive content for the panels' surface quality in case of coating and direct lacquering or a high content of coarse fibers in order to achieve low bulk densities intending to produce wood fiber insulation board.

4.5 Influence of wood species

The influence of wood species on the fiber size and further that of fiber size on panel properties were studied on Fibers B2 (pine), B4 (beech), B5 (mixture of pine and beech), B6 (birch) and B7 (poplar), manufactured within defibration series B. As can be seen from Table 3 and Fig. 1c, fibers

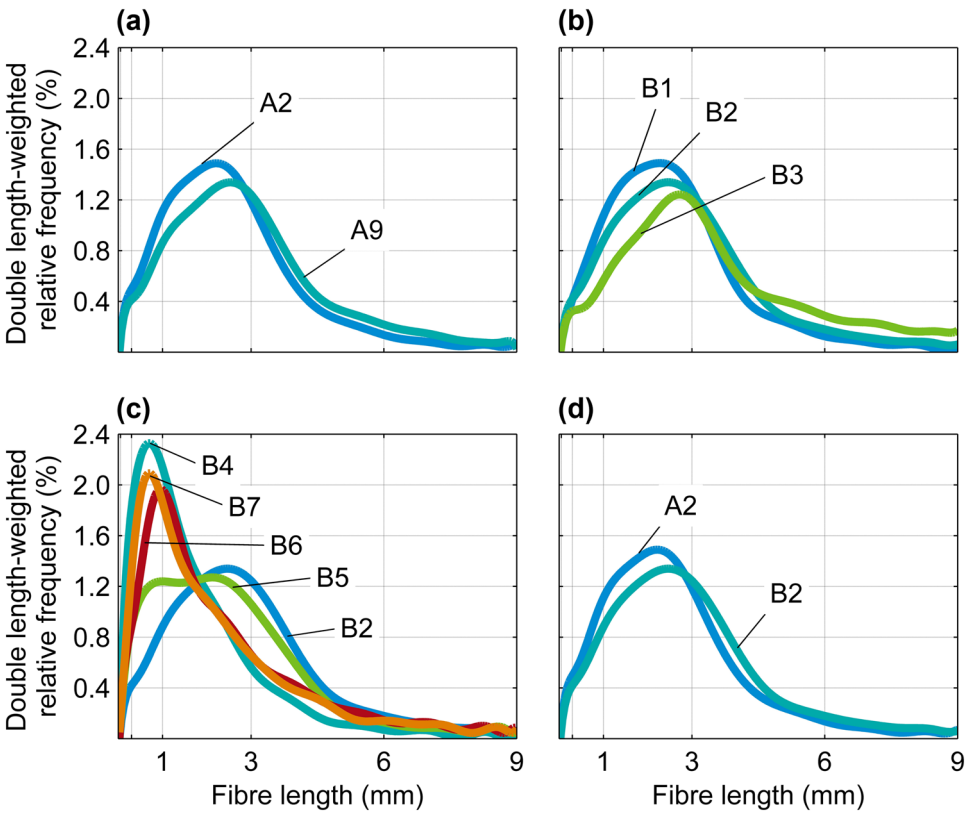

Fig. 1 Combinations of the double length-weighted fiber size distribution plots, illustrating the influence of **a** refiner discharging method, **b** grinding disc distance, **c** wood species and **d** wood chip size (pine) on the fiber quality. For more information regarding defibration parameters see Chapter 3.3 (fiber manufacturing)

from pine were found to be coarser (highest normalized number of fibers, longest double length-weighted fiber length, lowest double length-weighted relative frequency of short fibers) than fibers from hardwoods defibrated at equal process parameters. The fiber length and fiber length distribution of the hardwood fibers were found to be quite similar, while the double length-weighted fiber lengths of beech were found to be significantly shorter, followed by poplar. The extra fineness of beech fibers continues for the double length-weighted relative frequency, made obvious by significantly higher fine fibers and fines contents. The characteristics of fibers made of a pine and beech wood chip mixture were found to be a blending of pure pine and beech fibers.

A relationship between fiber length-based characteristic values and panel properties was not evident. The biggest differences were found between panels made of pine and poplar, and not between the most different fibers of pine and beech. However, it becomes obvious in sum that the variation of wood species results in changed fiber size, which affects panel properties.

Similar findings were made by Krug and Mäbert (2008) and Mäbert (2009), who investigated the usability of hardwoods as an alternative raw material source for MDF manufacturing. In this context, various wood species were defibrated, fiber size determined applying an air-jet sieve and test panels produced. It was found that the uses of different wood species for MDF manufacture result in different fiber sizes and in consequence different panel properties. The properties of panels made of fiber mixtures of different wood species were found to be a blend of the properties of panels made of fibers manufactured of only one wood species. This relationship fits well to the findings of fiber size determination in this study.

In addition to the finding that the fiber length distribution of fibers made of a pine and beech wood chip mixture were found to be a blending of pure pine and beech fibers, Ohlmeyer et al. (2014) showed that the combined analysis of measurement data from pure pine and pure beech fibers analysis results in nearly congruent curves displaying the double length-weighted relative frequency of fiber length.

4.6 Reproducibility of the same fiber quality

Because chipping and fiber manufacturing has to be arranged in two series (A and B), two fibers of identical quality were intended to be produced in order to serve as reference. Both fibers—A2 and B2—were manufactured at the same nominal defibration conditions: pine wood chips were steamed for 4 min at 170 °C and defibrated with a grinding disc distance of 0.15 mm.

Although the two fibers would have to be identical given the defibration conditions, Fiber B2 was found to be much coarser than Fiber A2 as can be seen from Table 3 and Fig. 1d. Accepting that defibration conditions were carefully set and that an insufficiently adjusted grinding disc distance can be excluded as influencing parameter, differences in raw material characteristics can be suspected as a reason for differences in fiber size characteristics.

During wood chip size characterization, unintended differences between the two defibration series were found. Wood chips for the first defibration series (Fiber A2) were found to be finer than those of the second defibration series (Fiber B2). Looking further at fiber size, Fiber A2 was found to be finer than Fiber B2. It seems reasonable to conclude that the wood chip size influences the fiber size because in case of smaller wood chips the structural elements of wood (fibers) are cut statistically more often. This assumption is confirmed by the fact that identically defibrated wood chips from beech—the one manufactured in chipping and defibration series A and the other in chipping and defibration series B—are in accordance with this interrelation. Fiber B4 was found to be finer than Fiber A8 (Table 3 and Fig. 2f), while at the same time the wood chips from Chipping series B were finer than those of Chipping series A (Table 2). An apparent influence on the panel properties was not observed.

5 Conclusion

The major aim of this study was to investigate the influence of defibration parameters on fiber size. Until now, fiber size evaluation had to be done by visual and manual fiber inspection because no adequate measuring system was available on the market. The use of the fiber size measuring system FibreCube enables an automated analysis of wood fiber samples, and thus a fiber size characterization by key figures and graphical representation. As a secondary objective of this study, the potential influences of fiber size on MDF properties were investigated.

It was found that wood species and grinding disc distance are the most influential parameters on fiber size. As can be expected from anatomical differences between hardwood and softwood, the fibers made of hardwoods were found to be much shorter than fiber made of wood chips from pine. Differences between fibers from various hardwoods (beech, birch, poplar) have been identified by fiber size analysis. In addition, wood species as well as the size distribution of the wood chips affect the resulting fiber size. Further grinding disc distance was found to strongly influence fiber size. The smaller the distance between the refiner discs, the finer the resulting fibers. Especially the content of fiber bundles (shives) was found to correlate with the grinding disc distance. This corresponds with common knowledge from haptic and visual fiber

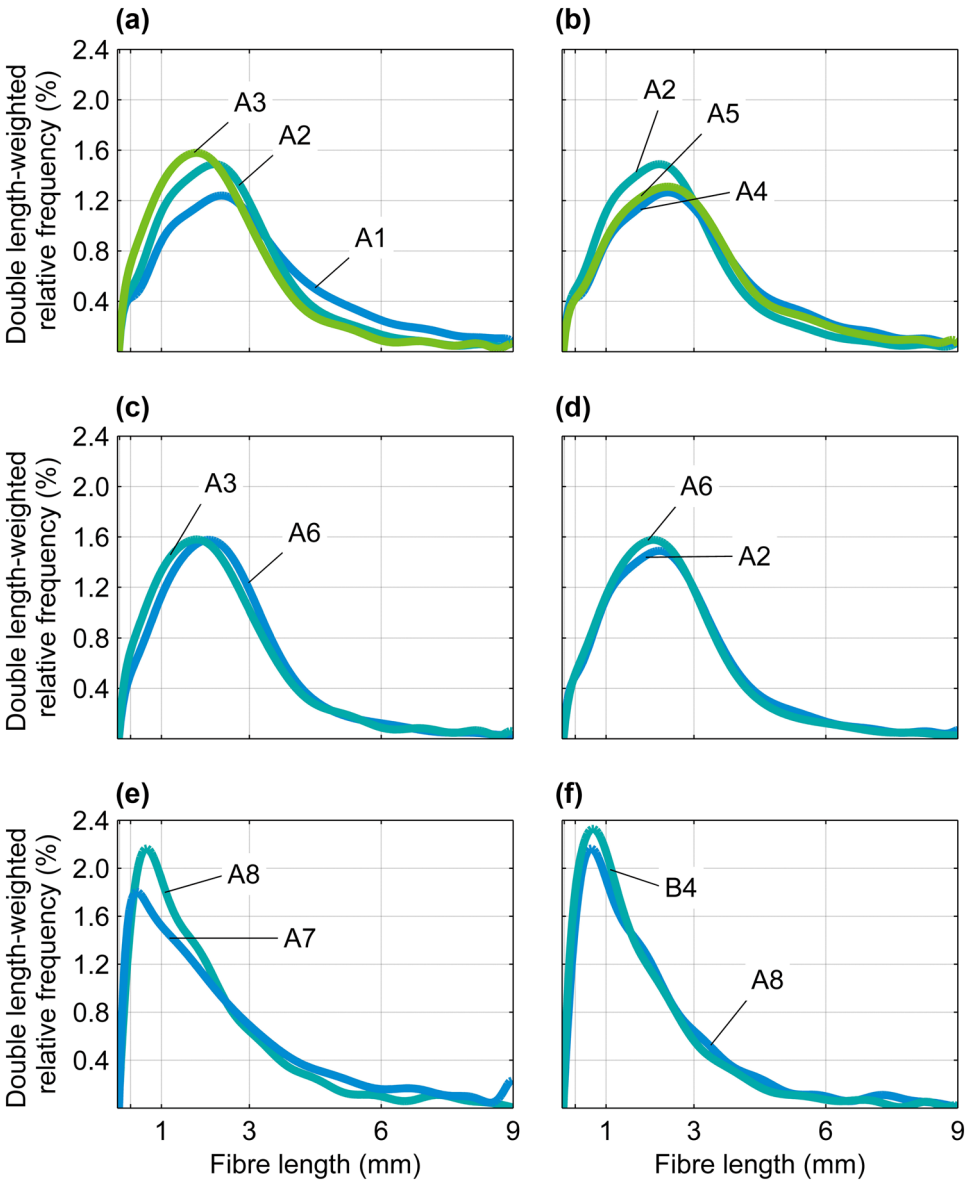

Fig. 2 Combinations of the double length-weighted fiber size distribution plots, illustrating the influence of **a** steaming time and temperature, **b** steaming time at 170 °C, **c** steaming time at 200 °C, **d** steaming temperature at a steaming time of 4 min (pine), **e** steaming temperature at a steaming time of 4 min (beech) and **f** wood chip size (beech) on the fiber quality. For more information regarding defibration parameters see Chapter 3.3 (Fiber manufacturing)

characterization in industrial practice according to which fiber quality is regulated by adjusting the grinding disc distance in order to achieve coarser or finer fibers and is now proven by numbers. In the case of an extreme simultaneous variation in steaming conditions, time and temperature, the visual fiber inspection suggests an effect of temperature exposure, as can be seen from fiber darkening with increased temperature and time. Further on, fiber length decreased with increasing steaming temperature and time. It became obvious from this investigation that the manufacture of test fibers has to be done with particular care in order to avoid unintended changes of the grinding disc distance due to thermal material expansion as a result of varied steaming parameters. Such unintended changes of the defibration parameters may superpose the effects of varied parameters which should initially have been investigated.

The influence of fiber size on the physical and mechanical panel properties was most dominant when steaming temperature and time were varied simultaneously. Panel properties worsen with intensified steaming conditions. Although fiber length was likewise found to decrease with intensified steaming conditions, fiber length cannot be assumed to be the only influencing parameter on panel properties. This becomes obvious when taking panel properties made of fibers at varied grinding disc distances into consideration. A comparably close correlation between fiber length and panel properties was not observed in this case. This implies that not only fiber size affects panel properties, but rather, it is more the chemical

nature of the fiber which is responsible for its wettability with water (thickness swelling) and glue (mechanical properties). This relationship is also implied by decreased thickness swelling with increased steaming temperature for all test panels.

This study showed that fiber lengths could automatically be determined without restrictions regarding the wood fiber sample character by applying the image analysis-based fiber size measuring system FibreCube. Fiber size characteristics can be specified as numerical key figures and thus used for the investigation of the influence of defibration conditions on fiber size, and further, fiber size on fiberboard properties.

Acknowledgments The authors would like to thank Mr. Christian Lanvermann, Eidgenössische Technische Hochschule Zürich (ETH), Institute for Building Materials, Wood Physics, Zurich, Switzerland, for programming the basis of the MatLab routine and Mr. Reiner Ohrnberger and Florian Lösch (both Norske Skog Walsum GmbH, Duisburg-Walsum, Germany) for the characterization of the wood chips. The financial support of Fachagentur Nachwachsende Rohstoffe e.V. (FNR) on behalf of the Federal Ministry of Food and Agriculture (BMEL) is gratefully acknowledged.

References

Asplund A (1939) Defibratormetoden och dess användningsområden. The defibrator method and its field of application. Teknisk Tidskrift 69(Kemi): 81–85 and 89–94

Benthien JT, Hasener J, Pieper O, Tackmann O, Bähnisch C, Heldner S, Ohlmeyer M (2013) Determination of MDF fiber size distribution: requirements and innovative solution. In Proc of the International Wood Composites Symposium 3.-4. April 2013, Seattle, Washington (WA), USA

Benthien JT, Heldner S, Ohlmeyer M (2014a) The characterization of TMP fibres in MDF. Wood Based Panels Int 1:26–27

Benthien JT, Wallot G, Seppke B, Heldner S, Gusovius HJ, Ohlmeyer M (2014b) Image based characterization of natural fibers: a comparison of measuring systems. Poster presentation at 10th International Symposium "Materials made of Renewable Resources" (naro.tech), 16–17 September, Erfurt, Germany

Benthien JT, Bähnisch C, Heldner S, Ohlmeyer M (2014c) Effects of fiber size distribution on medium-density fiberboard properties caused by varied steaming time and temperature of defibration process. Wood Fiber Sci 46(2):175–185

Deppe HJ, Ernst K (1996) MDF—Mitteldichte Faserplatte (MDF—Medium density fiberboards) (In German). DRW-Verlag Weinbrenner GmbH & Co., Leinfelder-Echterdingen

Döry L (2012) European Panel Markets and challenges for the industry. In Proc. of the 8th European Wood-Based Panels Symposium 10–12. October 2012, Hanover, Germany

Esteves BM, Pereira HM (2009) Wood modification by heat treatment: a review. Bioresources 4(1):370–404

FAO (2010) FAO Yearbook of Forest Products 2010. Food and Agriculture Organization, Rome, Italy, 2012, p 327

Funk S (2013) Online Analyse der Fasereigenschaften in der MDF Produktion zur Optimierung der Prozessstabilität und Energieeffizienz. [Online analysis of the fiber properties in the MDF production to optimize the process stability and energy efficiency]. Master thesis Hamburg University, Hamburg, Germany

Gran G, Bystedt I (1973) Latest developments in pressurized-refining with Defibrator equipment. Proc of the 7th W.S.U. Symp. Particleboard, Pullman, USA

Groom LH, Mott L, Shaler SM, Pesacreta T (1997) Effect of fiber surface and mechanical properties on the stiffness and strength of medium-density fiberboard. Proceedings of the International Association of Wood Anatomists/International Union of Forestry Research Organizations, November 1997. Westport, New Zealand, pp 375–387

Groom L, Mott L, Shaler S (1999) Relationship between fiber furnish properties and structural performance of MDF. 33rd International Particleboard/Composite Material Symposium 1999, 13-15 April 1999, Pullman, Washington, USA

Groom L, Rials T, Snell R (2000) Effects of varying refiner pressure on the mechanical properties of loblolly pine fibres. 4th European Panel Products Symposium 2000, 11–13 October 2000, Llandudno, North Wales, UK

Groom L, So C, Rials T,Alexander J, Neese J (2001) The structural performance of MDF: raw materials, refiner pressure, and resin formulation effects. 5th European Panel Products Symposium 2001, 10–12, October 2000, Llandudno, North Wales, UK

Groom L, So CL, Rials T, Neese J, Alexander J (2002) Relationships between wood quality, refiner pressure, and resin distribution and their influence on MDF panel properties. 6th European Panel Products Symposium 2002, 9.-11. October 2002, Llandudno, North Wales, UK

Hasener J (2013a) Inline Faserchararkterisierung—Traum oder Realität. [Inline fiber characterization—dream or reality]. In Proc of the 4. Innovationsworkshop Holzwerkstoffe, Köln, Germany, 14. Mai 2013

Hasener J (2013b) Inline Faserchararkterisierung, kein Traum sondern Realität—erste Praxiserfahrungen. Inline fiber characterization, no a dream but reality—first practical experiences. In: Proc. of the 3rd GreCon-Holzwerkstoffsymposium 2013, Magdeburg, Germany, 19–20, September 2013

Ibrahim Z, Aziz AA, Ramli R, Mokhtar A, Lee SJ (2013) Effect of refining parameters on medium-density fibreboard (MDF) properties from oil palm trunk (*Elaeis guineensis*). Open J Compos Mater 3:127–131

Jensen U, Seltmann J (1969) Untersuchungen zur trockenen Fraktionierung von Holzfaserstoffen. (Investigations on the dry fractionation of wood fiber materials). Holztechnologie 10(1):29–32

Kehr E (1977) Verfahren zur Herstellung von Faserplatten mittlerer Dichte, MdF. (Methods for the manufacture of fiberboards of medium-density, MDF).Holztechnologie 18:67–76

Kehr E, Jensen U (1971) Verfahrenstechnologie Mitteldichte Faserplatte. Einfluß der Faserstoffqualität in Deck- und Mittelschicht. [Process technology medium-density fiberboard. Influence of fiber quality in face and core layer]. Unpublished R&D report, Institut für Holztechnologie, Dresden, Germany

Krug D (2010) Einfluss der Faserstoff-Aufschlussbedingungen und des Bindemittels auf die Eigenschaften von mitteldichten Faserplatten (MDF) für eine Verwendung im Feucht- und Außenbereich. (Influence of defibration conditions and binding agent on the properties of medium-density fiberboard (MDF) for moisture exposed and exterior application). Dissertation thesis, Hamburg University, Hamburg, Germany, p 293

Krug D, Mäbert M (2008) Verwendung von Laubholz als Rohstoffalternative zur MDF-Herstellung. [Application of hardwood as raw material alternative for MDF production]. Institut für Holztechnologie gGmbH (IHD). Dresden (IW050353)

Lu JZ, Monlezun CJ, Wu Q, Cao QV (2007) Fitting weibull and lognormal distributions to medium-density fibreboard fiber and wood particle length. Wood Fib Sci 39(1):82–94

Mäbert M (2009) Fibre characterization in the wood-based materials industry—theory and reality. PTS Pulp Symposium 24–25, November 2009

Mäbert M, Krug D (2009) Tangential versus radial. MDF-Magazin 2009, pp 64–67, DRW-Verlag Weinbrenner GmbH & Co., Leinfelder-Echterdingen, Germany

Micko MM, Yanchuk AD, Wang EIC, Taylor FW (1982) Computerised measurement of fibre length. IAWA Bull 3(2):111–113

Myers GC (1983) Relationship of fiber preparation and characteristics to performance of medium-density hardboards. For Prod J 33(10):43–51

Ohlmeyer M, Hasener J, Schmid H (2006) New methods to determine fibre quality for MDF-production. 10th European Panel Products Symposium (EPPS), 11–13, October 2006, Llandudno, Wales, UK

Ohlmeyer M, Benthien JT, Heldner S, Seppke B (2014) FibreCube—an innovative approach to measure fibre size. 9th European Wood-based Panels Symposium (EWBPS) 08–10. October 2014, Hannover, Germany

Ohlmeyer M, Benthien JT, Heldner S, Seppke B (2015a) FibreCube How to Measure Fibre Size Distribution. InWood2015, 19–22, May 2015, Brno, Czech Republic

Ohlmeyer M, Benthien JT, Heldner S, Seppke B (2015b) Effects of Refining Parameters on Fibre Quality Measured by FibreCube. International Panel Products Symposium 2015, 7–8, October 2015, Llandudno, North Wales, UK

Plinke B, Schirp A, Weidenmüller I (2012) Methoden der Holzpartikelgrößenmessung—Von der technologischen Fragestellung zur aussagekräftigen Statistik. (Methods of wood particle size measurement—from the technological question to a meaningful statistic). Holztechnologie 53(4):11–17

Popp M (2013) Neue Möglichkeiten zur Analyse kreuzliegender Fasern mit FiVer. (New opportunities for the analysis of crosswise overlapping fibers with FiVer). Arbeitskreis Faseranalytik 2013, 11. September 2013, Hannover, Germany

Quirk JT (1981) Semiautomated recording of wood cell dimensions. For Sci 27(2):336–338

Roffael E, Dix B, Bär G, Bayer R (1994a) Über die Eignung von thermo-mechanischem und chemo-thermomechanischem Holzstoff (TMP und CTMP) aus Buchen- und Kiefernholz für die Herstellung von mitteldichten Faserplatten (MDF). Teil 1: Aufschluß des Holzes und Eigenschaften der Faserstoffe. (On the suitability of thermo-mechanical and chemo-thermo-mechanical pulps (TMP and CTMP) from beech and pine for the manufacture of medium density fibreboards Part 1: Pulping of wood and properties of the pulps) Holz Roh- Werkst 52:239–246

Roffael E, Dix B, Bär G, Bayer R (1994b) Über die Eignung von thermo-mechanischem und chemo-thermomechanischem Holzstoff (TMP und CTMP) aus Buchen- und Kiefernholz für die Herstellung von mitteldichten Faserplatten (MDF). Teil 2: Eigenschaften von MDF aus Buchen-Faserstoff. (On the suitability of thermo-mechanical and chemo-thermo-mechanical pulps (TMP and CTMP) from beech and pine for the manufacture of medium density fibreboards. Part 2: Properties of medium density fibreboards from beech pulps) Holz Roh- Werkst, 52:293–298

Roffael E, Dix B, Bär G, Bayer R (1995) Über die Eignung von thermo-mechanischem und chemo-thermomechanischem Holzstoff (TMP und CTMP) aus Buchen- und Kiefernholz für die Herstellung von mitteldichten Faserplatten (MDF). Teil 3: Eigenschaften von aus Kiefern-Faserstoff hergestellten MDF. (On the suitability of thermo-mechanical and chemo-thermo-mechanical pulps (TMP and CTMP) from beech and pine for the manufacture of medium density fibreboards Part 3: Properties of MDF from pine wood) Holz Roh- Werkst 53:8–11

Roffael E, Dix B, Schneider T (2001) Thermomechanical (TMP) and Chemo-Termomechanical Pulps (CTMP) for Medium Density Fibreboard (MDF). Holzforschung 55:214–218

Roffael E, Bär G, Behn C, Dix B (2009) Einfluss der Aufschlusstemperatur auf die morphologischen Eigenschaften von TMP aus Kiefernholz. (Effect of pulping temperature on the morphological properties of TMP made from pine wood). Eur J Wood Prod 67:119–120

Schiegl C (2004) Quantifizierung von Lignin aus Papierabwässern mittels Py-GC/MS und UV/VIS. (Quantification of lignin from paper production waste water by Py-GC/MS and UV/VIS). Dissertation, Technical University of Munich, Germany, p 122

Schmid H (2013) Neues über Fibreshape. (News about Fibreshape). Benutzertreffen Fibreshape 2013. Institute for Bioplastics and Biocomposites (IfBB), University of Applied Sciences and Arts Hannover, Hannover, Germany

Schneider T (1999) Untersuchungen über den Einfluss von Aufschlussbedingungen des Holzes und der Fasertrocknung auf die Eigenschaften von mitteldichten Faserplatten. (Investigations on the influence of the defibaration conditions of the wood and fiber trying on the properties of medium-density fiberboards). Dissertation thesis, Georg-August-Universität Göttingen, Shaker Verlag, Aachen, Germany, p 84

Schneider T, Roffael E (2000) Einfluß von Holzaufschlußverfahren (TMP-, CTMP-Verfahren) und Aufschlußbedingungen auf die physikalisch-technologischen Eigenschaften von mitteldichten Faserplatten (MDF). (Influence of wood defribration method (TMP, CTMP process) and process parameters on the physical-technological properties of medium-density fiberboards (MDF)). Holz Roh- Werkst 58:123–124

Schneider T, Roffael E, Windeisen E, Wegener G (2004) Einfluss der Aufschlusstemperatur auf lösliche Kohlenhydrate bei der TMP-Herstellung. (Influence of defibration temperature on soluble carbonhydrates in the manufacture of TMP). Holz Roh Werkst 62:321–322

Seppke B, Bähnisch C, Benthien JT, Heldner S, Ohlmeyer M (2015) A Concurrent Skeleton-based Approach for the Characterization of Wood Fibers with Sub-pixel Precision For Fiber Board Production. International Conference on Mass Data Analysis of Images and Signals (MDA) 11–24, July 2015, Hamburg, Germany

Shi JI, Zhang SY, Riedl B (2006) Multivariate modeling of MDF panel properties in relation to wood fiber characteristics. Holzforschung 60:285–293

Sliseris J, Andrä H, Kabel M, Wirjadi O, Dix B, Plinke B (2016) Estimation of fiber orientation and fiber bundles of MDF. Mater Struct. doi:10.1617/s11527-0150769-1

Wagenführ et al. (2008) Taschenbuch der Holztechnik. [Pocket book of the wood technology]. Carl Hanser, München, Germany

Weber A, Rapthel A, Sonntag U (2014) Echtzeit-Charakterisierung von Holzpartikeln für die Qualitätssicherung und Prozessoptimierung bei der Herstellung von Holzpartikelwerkstoffen in der Holzwerkstoffindustrie—Quick Wood-Particle Size. (Real time characterization of wood particles for the quality assurance and process optimization in the production of wood particle-based materials in the wood-based panel industry). Institut für Holztechnologie gGmbH (IHD), Dresden, Final Report 383 ZBR

Wenderdel C, Krug D (2012) Untersuchungen zum Einfluss der Aufschlussbedingungen auf die morphologische Ausprägung von aus Kiefernholz hergestellten TMP-Faserstoff. (Investigation of the influence of pulping parameters on morphological characteristics of TMP-pulp made from Scots pine). Eur J Wood Wood Prod 70:85–89

Wenderdel C, Hesse E, Krug D, Hänsel A, Niemz P (2013) Influence of surface roughness of wood fibres on properties of medium density fibreboards. Pro Ligno 9(4):423–429

Wenderdel C, Weber A, Pfaff M, Sonntag U, Theumer T (2014) Spezielle Methoden zur morphologischen Charakterisierung lignocelluloser Faserstoffe—Teil 1: Stand der Technik und theoretische Ableitung einer Partikelklassifizierung. (Special techniques for the morphological characterization of lignocellulosic fibers—Part 1: state of the art and theoretical derivation of a particle classification). Holztechnologie 55(6):12–19

Wessbladh A, Mohr R (1999) Faserfeinheiten: Moderne Analysemethoden liefern Online-Qualitätsindizes. (Fiber fineness: modern analysis methods provide online quality indices). MDF-Magazin, DRW-Verlag Weinbrenner GmbH & Co, Leinfelden-Echterdingen, Germany

Xing C, Deng J, Zhang SY, Riedl B, Cloutier A (2006) Properties of MDF from black spruce tops as affected by thermomechanical refining conditions. Holz Roh Werkst 64:507–512

Xing C, Wang S, Pharr GM, Groom LH (2008) Effects of thermomechanical refining pressure on the properties of wood fibers as measured by nanoindentation and atomic force microscopy. Holzforschung 62:230–236

Xing C, Wang S, Pharr GM (2009) Nanoindentation of juvenile and mature loblolly pine (*Pinus taeda L.*) wood fibers as affected by thermomechanical refining pressure. Wood Sci Technol 43:615–625