Effect of Tool and Milling Parameters on the Size Distribution of Splinters of Planed Native and Thermally Modified Beech Wood

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This paper deals with splinter size analysis of beech wood, considering the angular tool of the cutter and also the physical and mechanical wood properties substantially influencing wood processing technology. Particle size analysis was conducted by sieving the samples using a set of laboratory sieves, with subsequent determination of the individual fraction shares. The results have been compared with respect to the possibility of wood waste separation and filtration, and its subsequent utilization, above all, in the production of agglomerated materials and production of wood briquettes and pellets. The most frequently occurring fractions in native beech samples range between 5 and 8 mm and between 2 and 5 mm, while powder fractions below 125 μm were found in less than 1% of investigated samples. The most frequently occurring fractions in thermally modified beech wood ranged from 0.5 to 1 mm, and the share of powder wood particles below 125 μm was less than 4%.

Keywords: Plane milling; Splinter size analysis; Beech wood; ThermoWood; Cutting speed; Feed speed; Splinter size distribution

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INTRODUCTION

Wood is a naturally occurring substance and – like all natural materials – it has specific properties. Similarly, thermally modified wood has its specific properties, which are acquired in the course of thermal treatment. Therefore, the purpose of research was focused on milling of native and thermally treated wood in terms of the resulting splinters. Dimensions of the particles and the percentage of its fractions are important for filtering and cleaning equipment in the woodworking industry.

Thermally modified wood has been produced for almost 15 years on an industrial scale. Its production has been launched in a number of West European countries as the response to changing legislation in the chemical protection of timber. It was Finland that pioneered the production of thermally modified wood (under the ThermoWood trade mark). Later on, the production was also opened in the Netherlands, Austria, Germany, and France. Solely heat (combined with vapor or natural oils) is used for production without any toxic chemicals; hence, this is an environmentally friendly method not only in terms of production but also in application of this wood material, featuring longer durability compared with native wood both in interior and exterior.

Thermal wood modification is based on thermal and hydrodynamic wood treatment procedures at temperatures ranging from 150 to 220 to 260 °C. High temperatures cause the decomposition of specific construction timber polymers, creating new substances that are not water-soluble, and also substances that kill or repel biologic pest agents, such as moulds and decay fungi. Wood strength and certain mechanical properties of thermally modified wood become reduced (Požgaj *et al.* 1993; Yildiz *et al.* 2006; Mburu *et al.* 2008; Esteves and Pereira 2009). The influence on mechanical parameters is substantially less dramatic if thermal treatment of wood is conducted in an inert atmosphere, without oxygen, *e.g.* in vacuum or in the presence of nitrogen and oil (Reinprecht and Vidholdová 2008; Kubojima *et al.* 2000).

Changes to wood structure occur at temperatures as low as 20 to 150 °C, where wood becomes dry. Significant and also intensive chemical changes occur at temperatures ranging from 180 to 250 °C. Wood carbonization process starts at temperatures exceeding 250 °C, producing carbon monoxide and other combustion products (Kačíková and Kačík 2011). In addition to the plasticizing processes, dramatic changes in chemical structure of wood start at temperatures ranging from 150 to 170 °C. Polar groups -OH disappear in the polysaccharide, lignin structures of concomitant substances, and depolymerization and condensation reactions occur in connection with partial wood carbonization, liberating inflammable gases. Because of these changes, thermally modified wood becomes more resistant against biological pests, and its hydroscopic capacity becomes reduced (Reinprecht and Vidholdová 2008).

Thermal treatment of wood also changes its anatomical structure and properties. The changes occurring in anatomical structure influence final properties of the modified material. These changes are attributable, primarily, to changes in wood cells, first of all in cellular wall layers.

Milling means the process of machining wood using rotating tools (cutter, milling head, and shank cutter), in which nominal splinter thickness will be changed by depth of material removal, from minimum to maximum value in conventional (orthodox) milling processes, or from maximum to minimum value in climb feed milling processes. Width or shape of machined wood will also be changed.

Material feed is in the direction of circumferential speed vector of the rotating cutting tool (Fig. 1). In one rotation, the cutting tool is engaged at arch length l, corresponding to central angle $\varphi + \varphi'$. Value φ' is extremely small and, in most cases, it will be neglected in calculation of splinter length l (Lisičan 1988, 1996; Buda *et al.* 1983; Barcík *et al*. 2008a,b; Dzurenda 2009; Kvietková and Barcík 2011, 2012; Javorek and Oswald 1998).

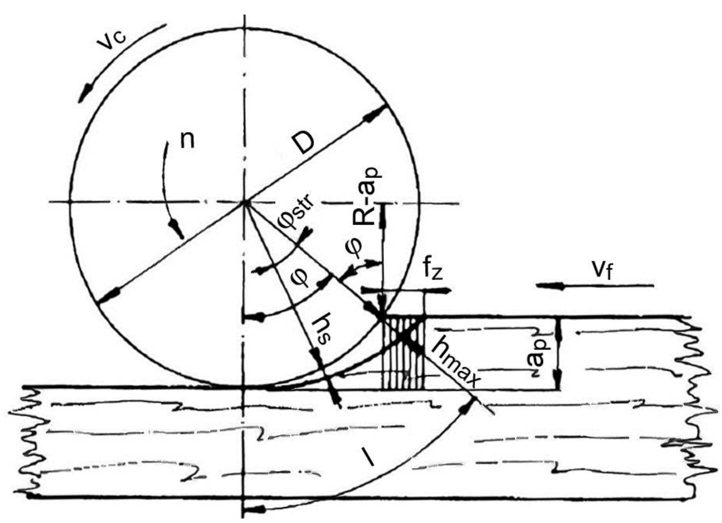

Fig. 1. Separation of splinters in a plane milling (Prokeš 1982)

EXPERIMENTAL

Materials

The experimental European beech trees (*Fagus sylvatica* L.) were 75 years old and grew in the central region of Czech Republic, near Kostelec nad Černými lesy, east of Prague. The zones suitable for samples were cut from the trunk at a height of 2.5 m from the stump. The zones, which were in the middle distance between the pith and bark, were chosen for sample preparation. From these parts were cut 200-cm long sections which contained 1.5-mm–wide annual rings. For the experiments, beech samples with dimensions of 40×100×1000 mm were used. All the samples were air-conditioned in the conditioning room (ϕ = 65 ± 3% and t = 20 ± 2 ºC) for more than six months to achieve an equilibrium moisture content (EMC) of 12%. The actual EMC of each sample was measured by a weighing method after conditioning.

A special group of beech samples have been prepared for identification of physical and mechanical properties of native and thermally modified wood. The dimensions of these samples were in compliance with relevant standards and these samples were only used for identification and verification of these properties.

All of the air-conditioned samples were divided into two groups for the investigation—samples of native beech wood and samples for thermal (thermo wood) treatment. The whole investigation contained 50 samples.

Procedure

Thermal treatment

Beech samples intended for thermal modification were put on a metal grate and subsequently placed into a thermal chamber (type 103/6200), produced by Hitwood Oy Finland (Fig. 3 *left*) (initial parameters are indicated in Table 1) and modified (see Fig. 2). Refer to Table 1 for times of all thermal treatment stages. Prepared and thermally modified samples were subsequently placed at a temperature of 20 °C and relative air humidity of 65% to allow for moisture stabilization.

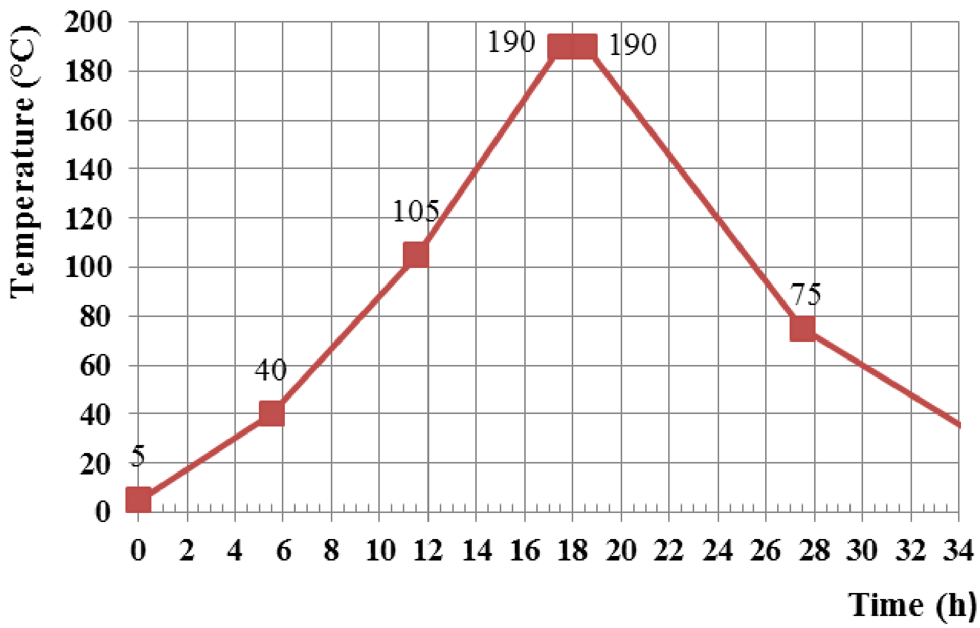

Fig. 2. Progress of thermal treatment

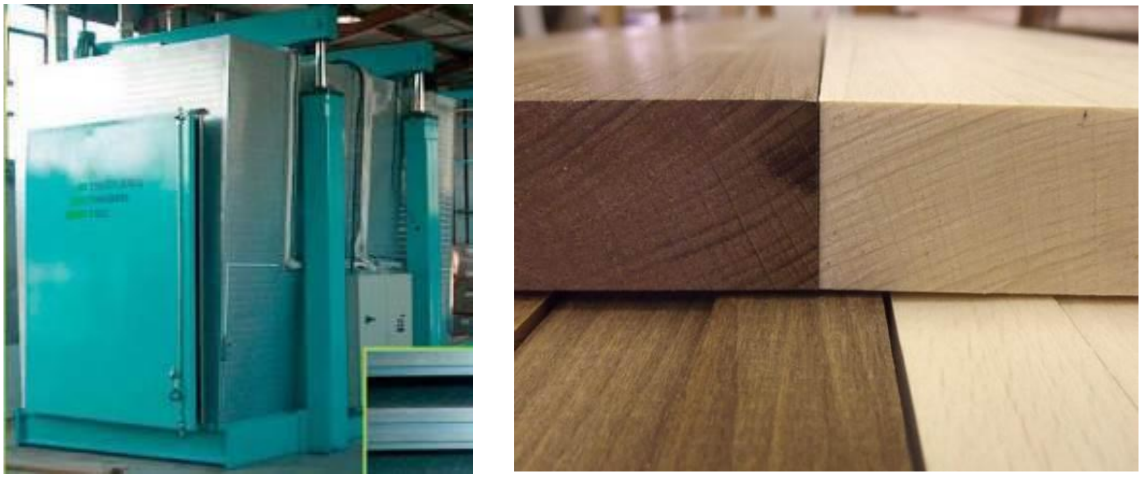

Fig. 3. Thermal chamber 103/6200 (*left*) and an overview of cross-sections of wood types (*right*)

Table 1. Conditions and Procedures for Thermal Treatment – Thermo Wood Preparation

Input Technical Parameters		Thermal Treatment Procedure	
Moisture content of wood	10.5 to 12 %	Heating	5.5 h
Filling capacity of TW furnace	7 m^3	Drying	6 h
Water consumption	885 L	Heating	6 h
Electricity consumption	2950 kWh	Thermal (TW) treatment	1 h
Maximum reached temperature	191 °C	Cooling	9 h
		Total time	27.5 h

All samples were then machined to final thickness (30 mm) using a thickness planer. Thus, planed native and thermal modified materials (final dimensions 30 × 100 × 1000 mm) (Fig. 3 *right*) were prepared for milling to obtain wood splinters for analysis.

Milling

The milling process was carried out using a one-spindle cutter (FVS) with a STEFF 2034 feeding system, produced by Maggi. Cutter parameters and also individual cutting angles (Fig. 4) are listed in Table 2.

Table 2. Cutting Conditions for Milling

One-spindle cutter FVS (Ø 130 mm) with feed system STEFF 2034		Cutter Head	
Input power	4 kW	Rake angle γ	15, 20, and 25°
RPM	3000, 4500, 6000, and 9000	Cutting angle of wedge β	45°
Cutting speed	20, 30, and 40 m/s	Clearance angle α	20, 25, and 30°
Feed speed	4, 8, and 11 m/min	Cutting angle δ	70, 75, and 80°

α – clearance angle

β – cutting angle of wedge

γ – rake angle

δ – cutting angle

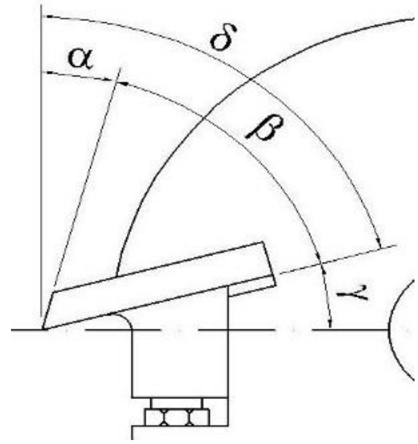

Fig. 4. The angles of the cutting blades fitted in cutter head (Prokeš 1982)

Granulometrical (sieving) analysis

Sieve analysis was carried out on a vibratory sieving machine (Retsch AS 200, Fig. 5), with a sieving time of 5 min and breaks every 10 s. The machine was equipped with sieves with mesh sizes of 0.032, 0.080, 0.125, 0.250, 0.5, 1, 2, 5, and 8 mm, and bottom-sieves were used in accordance with ISO 3310-1 (2000).

Fig. 5. Vibratory sieving machine Retsch AS 200

Evaluation and Calculation

The density was determined as an auxiliary indicator. Density was calculated according to Eq. 1 from ISO 3131 (1975),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density of the test sample at certain moisture content w [kg/m^3], m_w is the mass (weight) of the test sample at certain moisture w [kg], a_w, b_w, and l_w are dimensions of the test sample at certain moisture w [m], and V_w is the volume of the test sample at a certain moisture w [m^3].

The density of wood after treatment was calculated according to Eq. 2 from ISO 3131 (1975),

$$\rho_{tw} = \frac{m_{tw}}{a_{tw} * b_{tw} * l_{tw}} = \frac{m_{tw}}{V_{tw}} \tag{2}$$

where ρ_{pl} is the density of the test sample after treatment [kg/m^3], m_{pl} is the mass (weight) of the test sample after treatment [kg], a_{pl}, b_{pl}, and l_{pl} are dimensions of the test sample after treatment [m], and V_{pl} is the volume of the test sample after treatment [m^3].

Maximum bending strength in static bending was determined as an additional factor, which varies due to thermal treatment. Bending strength was calculated according to Eq. 3 from ISO 3133 (1975),

$$\sigma_w = \frac{3.F_w.l_w}{2.b_w.d_w^2} \tag{3}$$

where σ is the bending strength of the test sample at certain moisture content w [MPa], F_w is the load force at the fraction point of the test sample at certain moisture content w [N], l_w is the length of support span of the test sample at certain moisture content w [mm], b_w is the width of the test sample at certain moisture content w [mm], and d_w is the thickness of the test sample at certain moisture content w [mm].

The maximum bending strength of wood after treatment was also calculated according to Eq. 4 from ISO 3133 (1975),

$$\sigma_{tw} = \frac{3.F_{tw}.l_{tw}}{2.b_{tw}.d_{tw}^2} \tag{4}$$

where σ is the bending strength of the test sample after treatment [MPa], F_w is the load force at the fraction point of the test sample after treatment [N], l_w is the length of support span of the test sample after treatment [mm], b_w is the width of the test sample after treatment [mm], and d_w is the thickness of the test sample after treatment [mm].

The impact bending strength was determined as an additional factor, which varies due to thermal treatment. Impact bending strength was calculated according to Eq. 5 from ISO 3148 (1975),

$$A_w = \frac{Q}{S_w} \tag{5}$$

where A_w is the impact bending strength of samples at certain moisture content w [J/cm^2], Q is the work required for breaking the sample [J], and S is the cross-section area *(b × d)* of samples at certain moisture content w [cm^2].

Moisture content of samples was determined and verified before and after thermal treatment. These calculations were carried out according to ISO 3130 (1975) and Eq. 6,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{6}$$

where w is the moisture content of the samples [%], m_w is the mass (weight) of the test sample at a certain moisture w [kg], and m_0 is the mass (weight) of the oven-dry test sample [kg].

Drying to oven-dry state was also carried out according to ISO 3130 (1975), using the following procedure: The samples were placed in the drying oven at a temperature of 103 ± 2 ºC until a constant mass had been reached. Constant mass is considered to be reached if the loss between two successive weighing carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the sample was weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy at weighing should be at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

Average moisture of native beech wood was 10.5 %, which corresponds to wood moisture under conditions φ = 65 ± 3% and t = 20 ± 2 °C, *i.e.*, wood moisture should be approximately 12% (Peschel 2002; Horák 1996). Average moisture of thermally modified beech was 2.6%. Maulis (2009) and the ThermoWood Handbook (2002) indicate 4% moisture for thermally modified beech wood, at comparable conditions. In the ThermoWood Handbook (2003), moisture reduction of up to 50% compared with original moisture value has been claimed. The results of our investigation are provided in Table 1.

Table 3. Moisture Content of Native and Thermally Modified Beech Wood

Native Beech Wood		Beech Wood with Thermal Treatment	
Minimum value	9.9%	Minimum value	1.6%
Maximum value	10.6%	Maximum value	3.0%
Average value	10.5%	Average value	2.6%
Standard deviation	0.297	Standard deviation	0.526
Coefficient of variation	2.8	Coefficient of variation	20.6

The average density of native beech, measured by us, was 715 kg/m^3. This corresponds to the 720 kg/m^3 indicated by Prokeš (1982). The average density of thermally modified beech after 1-h exposure to temperature 190 °C was 686 kg/m^3. Hence, density of thermally modified beech wood is lower by 29 kg/m^3, *i.e.*, approximately 5% density reduction. This is primarily due to weight reduction. This fact has also been confirmed in ThermoWood Handbook (2002). Maulis (2009) indicates 10%

density reduction of thermally modified beech wood at the temperature of 210 °C, while Yildiz (2002b) reported a minor density increase for beech wood (2.25%) for treatments at 130 ºC for 2 h but mentioned that for treatments at higher temperatures (200 ºC - 10 h) density decreased by 18.37%. In relation to the density decrease, Boonstra *et al.* (2007) believed that the degradation of hemicelluloses into volatile products and the evaporation of extractives are the main reasons.

Static bending strength (MOR) was 120.2 MPa (average value). This result is comparable with the values indicated for bending strength of beech wood at 12% moisture. Prokeš (1982) indicates a bending strength value amounting to 123 MPa. Bending strength of thermally modified beech wood increased by 32.5 MPa, thus reaching 152.7 MPa. The increase in bending strength of thermally modified beech is approximately 25 % of that of native beech wood. This increase has been achieved owing to short period of applied temperature. According to the indicated data, "ThermoWood" modification technology results in unchanged or slightly increased bending strength in the case of a moderate treatment procedure (Thermo-S). Kubojima *et al.* (2000) reported that the bending strength increased in the beginning of the treatment, and decreased afterwards. The work needed for rupture decreased steadily with the time of treatment. The main factors contributing to the reduction of the work necessary for rupture were viscosity and plasticity, but not elasticity.

Measured and calculated results of impact bending strength showed reduced value for thermally modified beech, while average impact bending strength of native beech was approximately 10.8 J/cm^2. Average impact bending strength of thermally modified beech was reduced to 8.7 J/cm^2, *i.e.*, approximately 20% less than the original value. This reduction in value is less dramatic than what was indicated by various authors, *i.e.*, up to 50% (Maulis 2009). Lesser reduction of impact bending strength in wood samples investigated by us can be attributed to lower wood modification temperatures and also shorter times of exposure. Kubojima *et al*. (2000) also reported that impact (toughness) bending also increased in the beginning, lowering afterwards. Also, Esteves and Pereira (2009) stated that two of the most affected mechanical properties by the heat treatment are the resistance to bending in static (MOR) and dynamic tests (impact bending), because the reduction depends on wood species and process conditions. For example, the ThermoWood Handbook (2002) found that spruce, which had been treated for 3 h at 220 °C, had the impact strength reduced by about 25%

Cutting and Feed Speed

Change of cutting speed influences splinter size, mainly in combination with feed speed, since material feed speed is also considered in calculation of theoretical splinter size (Dzurenda 2002).

Cutting speed change at feed speed v_f = 4 m/min had no significant impact on splinter size distribution, as can be seen on Fig. 7. At all cutting speeds, 2 to 5 mm size fractions were the most frequent values in native wood, and 0.5 to 1 mm were the most frequent in thermally modified beech wood. Changes in the most frequent size fraction in thermally modified beech wood occured at cutting tool rake angle being 25°, where the most frequent fraction (approx. 36%) ranged from 1 to 2 mm at cutting speed v_c = 20 m/s. After increasing the cutting speed to v_c = 30 m/s, the most frequently occurring fraction (approx. 38%) was 0.5 to 1 mm. Further raising of the cutting speed to v_c = 40 m/s resulted in increasing the percentage of the 0.5 to 1 mm fraction (to 44 %).

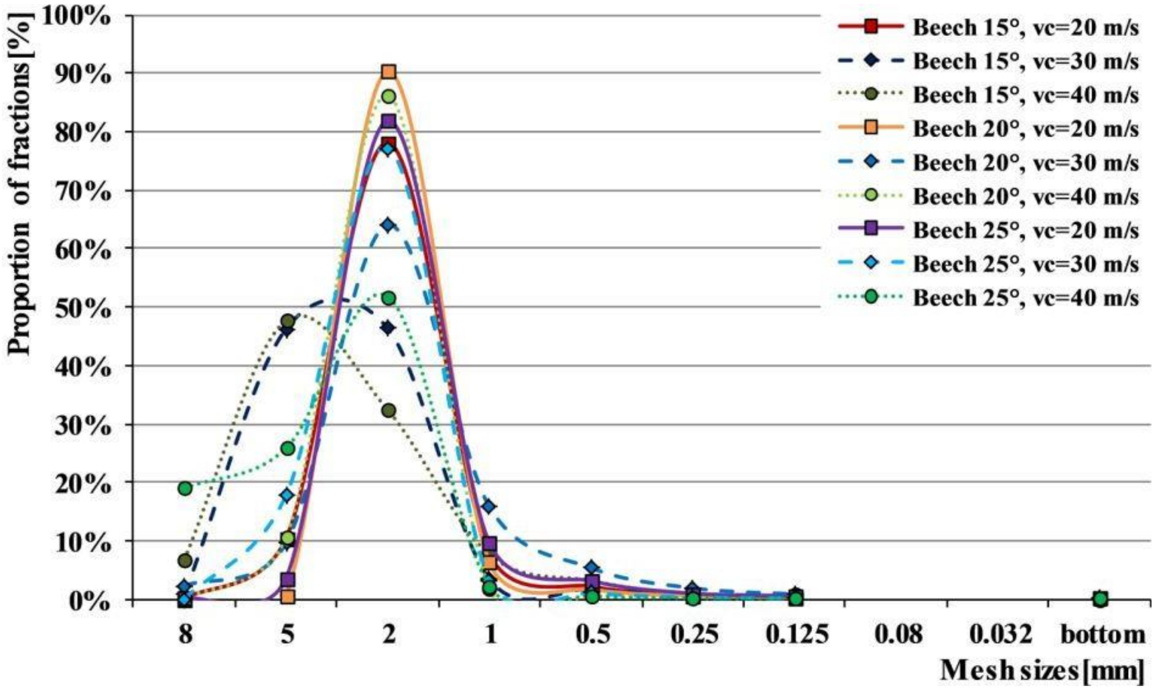

Fig. 6. Effect of cutting speeds on splinter size distribution of natural beech at feed speed v_f = 4 m/min

Similar changes could be seen in native beech at rake angle 15° and feed speed v_f = 4 m/min. At v_c = 40 m/s, the largest share (approximately 48 %) of splinters ranged 8 to 5 mm; after reduction of cutting speed to v_c = 30 m/s, the percentage did not change, however, it was transferred 2 to 5 mm splinter size range. Further reduction of the speed results in increasing the percentage of this fraction to aproximately 78%.

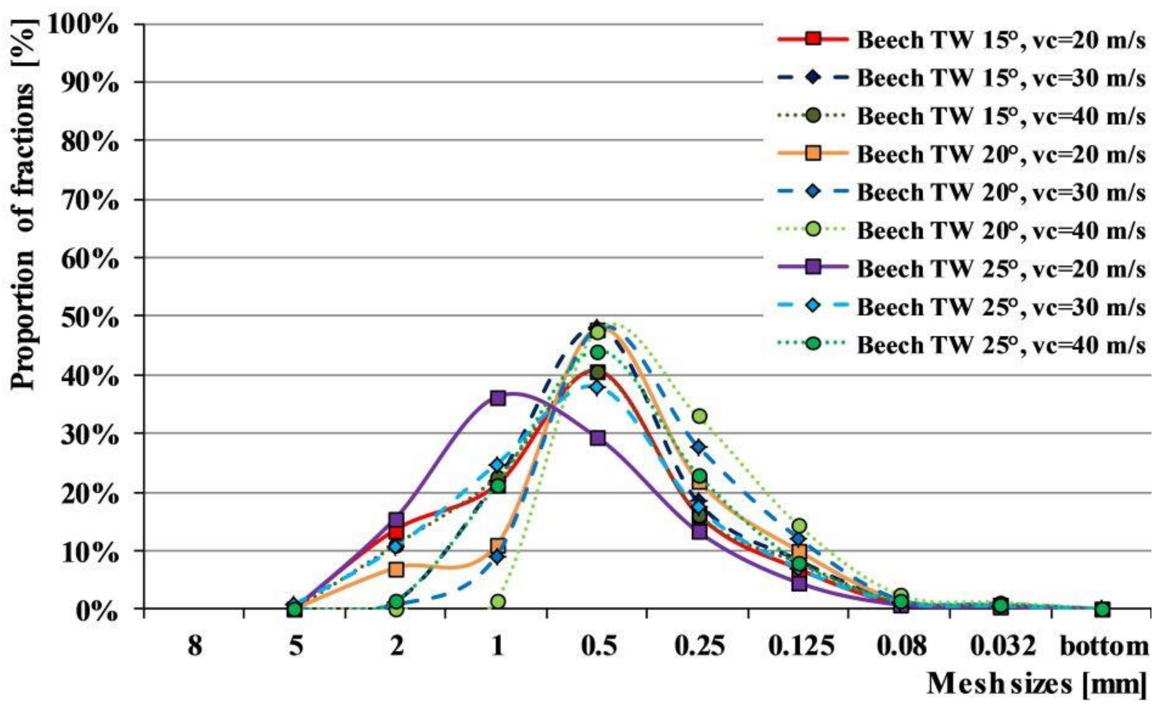

Fig. 7. Effect of cutting speed on splinter size distribution of TW beech at feed speed v_f = 4 m/min

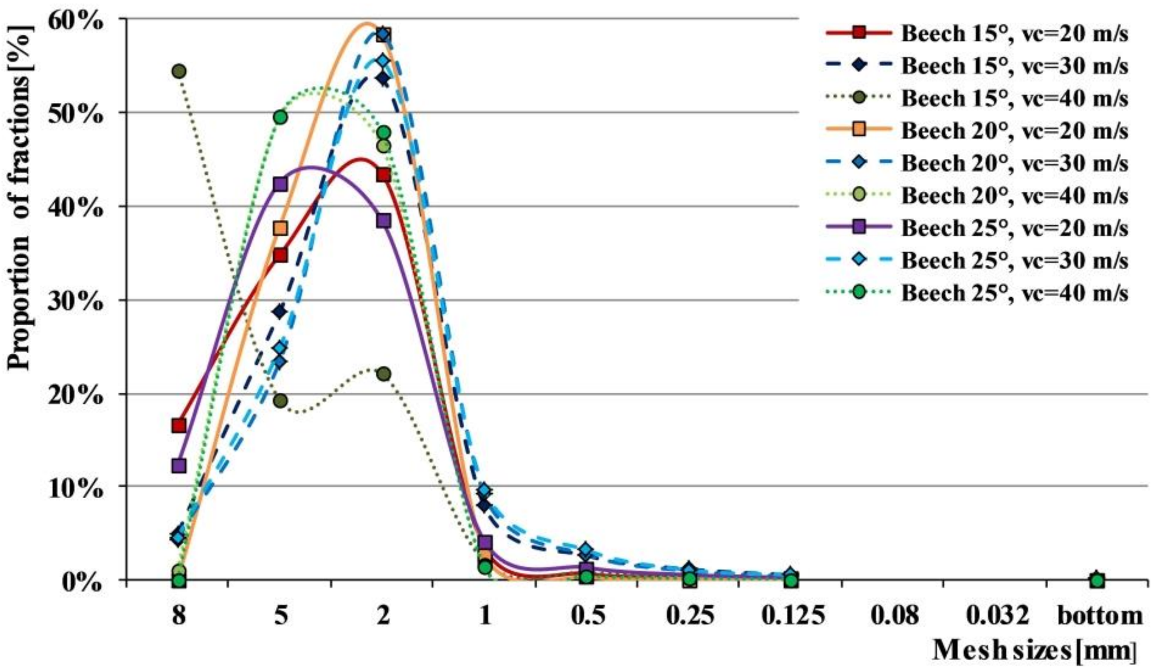

Fig. 8. Effect of cutting speed on splinter size distribution of natural beech at feed speed v_f = 8 m/min

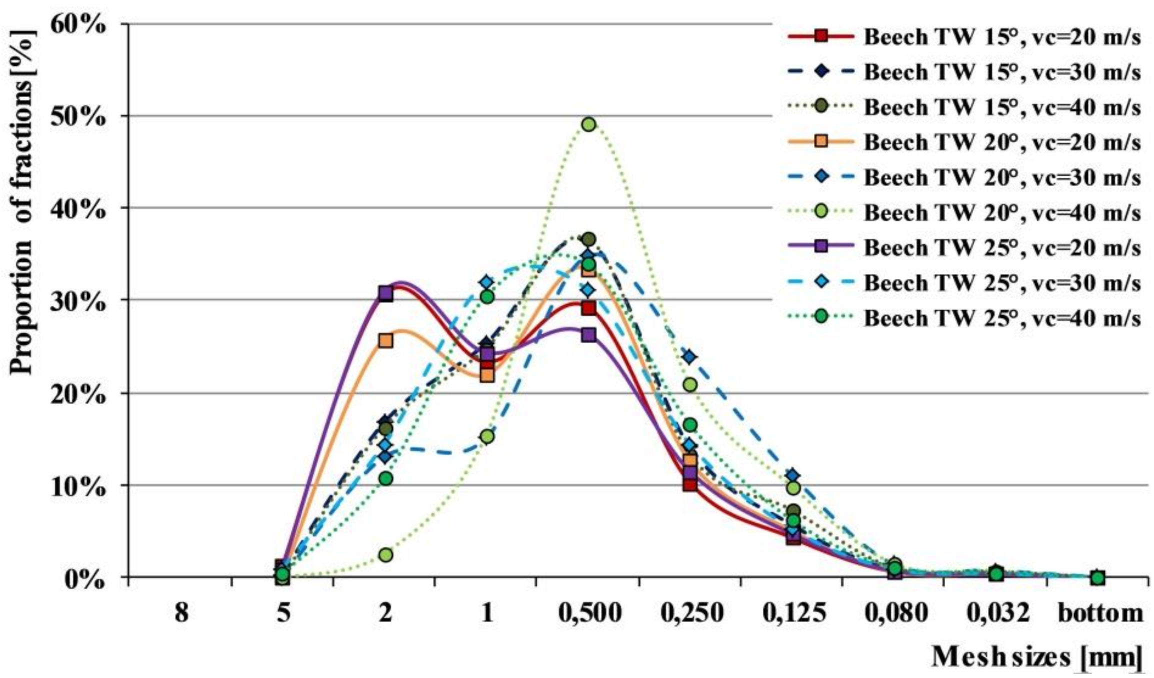

Fig. 9. Effect of cutting speeds on splinter size distribution of TW beech at feed speed v_f = 8 m/min

Other angle parameters did not result in changing the share of the biggesst fraction, but only to fraction size distribution. In native beech, the share of the most frequently occurring fraction increased from 52 to 90% with increasing cutting speed. Change in share of the fraction in thermally treated beech wood along with changing cutting speed was much less significant, ranging from 30 to 50%. Also, changed feed speed v_f = 8 m/min did not dramatically influence splinter size structure in natural beech, as can be seen in Fig. 8. The most frequently represented fraction was 2 to 5 mm, and changes were dependent on changing of cutting speed..

The share of the most frequent fraction ranges from 53 to 58% at cutting speed v_c = 30 m/s, regardless of cutting geometry. An exception is cutting speed v_c = 40 m/s and rake angle 15°, where the largest fraction (approx. 55 %) is more than 8 mm.

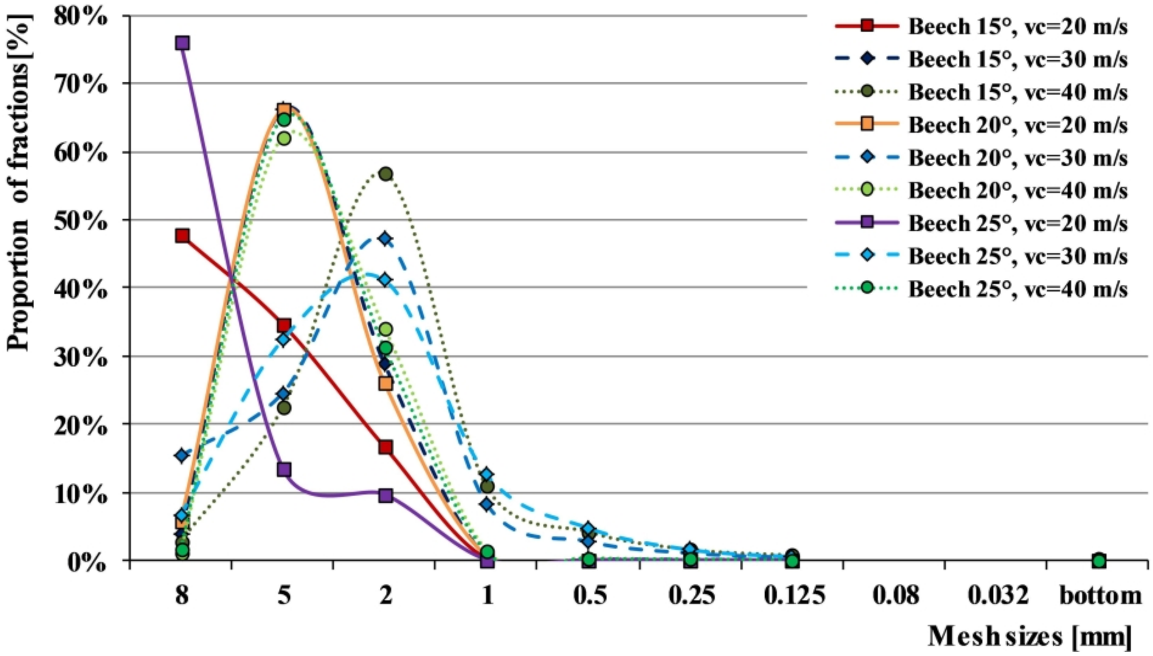

Fig. 10. Effect of cutting speeds on splinter size distribution of natural beech at feed speed v_f = 11 m/min

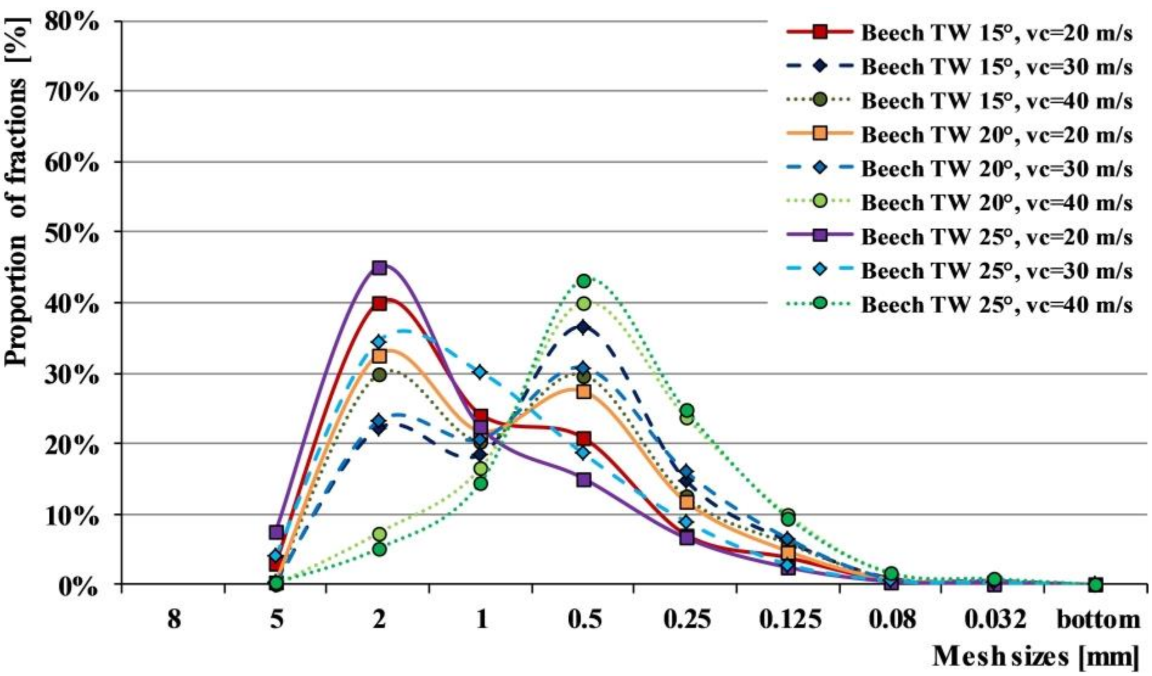

Fig. 11. Effect of cutting speeds on splinter size distribution of TW beech at feed speed v_f = 11 m/min

The influence of cutting speed change at feed speed v_f = 11 m/min was demonstrated, above all, by movement of the most frequently occurring fraction towards more coarse splinter sizes. In native beech, the most frequently occurring fractions (approximaely 65%) ranged from 5 to 8 mm at cutting speeds v_c = 40 m/s and v_c = 30 m/s (Fig. 10). An exception is v_c = 20 m/s at rake angles 15° and 25°, with the most frequent fraction exceeding 8 mm. In thermally modified beech wood, this change was even more significant. The largest sizes ranged from 0.5 to 1 mm at cutting speed v_c = 40 m/s. At cutting speed v_c = 20 m/s, the most frequently occurring sizes ranged between 2 and 5 mm, mainly at rake angle 25°.

Summarizing the results, it can be said that the splinters of thermally modified beech wood are finer and smaller. This fact has also been confirmed by other authors, *e.g.*, Dzurenda and Orlowski (2011), who investigated the splinters of thermally modified ash, and Dzurenda *et al*. (2010), who investigated splinters of thermally modified oak. The smaller size and finer splinter pattern can be attributed to changes in wood structure, which becomes more brittle due to the influence of thermal modification (Poncsák *et al*. 2006). Phuong *et al*. (2007) studied the effects of heat treatment on the brittleness of *Styrax tonkinensis* wood and concluded that the main factor affecting brittleness was the loss of amorphous polysaccharides due to degradation. On the other hand, the orientation of wood in the direction of planning has a direct influence on size of the splinters as well as its smoothness. This fact was confirmed by Söğütlü (2010a, 2010b), who investigated the impact of various feed speeds at planning on surface roughness of native beech and pine wood.

CONCLUSIONS

1. As documented by the results and graphs of particle size analysis, milling of thermally modified beech causes changes in splinter size distribution and also in the shares of individual fractions in comparison with native beech wood. These data are important for designing air exhaust systems and, above all, for modification of design and types of cleaning systems to suit to specific shares and types of splinter fractions.
2. For untreated beech wood, the most frequently occurring size fraction ranged between 2 and 5 mm at v_f = 4 m/min and between 5 and 8 mm at v_f = 11 m/min. For thermally modified beech wood, the most frequently occurring size fraction ranged from 0.5 to 1 at v_f = 4 m/min, whatever the cutting speed. After increasing the feed speed to v_f = 4 m/min, the most frequently occurring size fraction changes with changing cutting speed. At v_c = 40 m/s, it ranges from 0.5 to 1 mm, and at v_f = 20 m/s, the fractions ranging from 2 to 5 occur more frequently. Hence, the feed speed in combination with cutting speed has the most significant influence on the percentage and fraction size distribution of disintegrated wood substance. The strongest influence of the cutting speed could be recognized in the percentage of the biggest fraction, whereas the strongest influence of the feed speed could be seen in the percentage of the smallest fraction.
3. The differences between native and thermally modified wood splinters are comparatively small, as the smallest and the biggest splinter fractions are similar. Consequently, it is not necessary to use other types of cleaning equipment for milling

thermally modified wood, as is normal with exhaustion of native wood splinters at machining. For exhaustion of beech wood splinters during plane milling processes, fabric-filters, as well as mechanic separators allowing separation of small particles (separation limit 10 μm) can be used in filtration and cleaning systems to comply with environmental standards of separation of disintegrated wood substance from air. The separation limit is a specific parameter of the separator unit and indicates the size of the smallest "a" [μm] particles that can be separated using the relevant unit.

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