The Effect of Selected Technical, Technological, and Material Factors on the Size of Juvenile Poplar Wood Chips Generated during Face Milling

Marek Vančo,[a] Zuzana Jamberová,[a] Štefan Barcík,[a] Milan Gaff,[b,]* Hana Čekovská,[b] and Lukáš Kaplan [b]

The effects of technical, technological, and material factors affecting the size of juvenile poplar wood chips were evaluated. Each analysis was performed on two species of poplar, namely natural poplar *Populus tremula* L. and plantation poplar clones *Populus euramericana* Serotina, and on juvenile and mature wood within each poplar species. A cutter with angular geometry was selected for the face milling: β = 55° (angle of cutting wedge), γ = 15° (rake angle). The cutting conditions were a feed rate of v_f = 2.5 and 15 m·min^{-1}, cutting speed of v_c = 30 m·s^{-1}, 45 m·s^{-1}, and 60 m·s^{-1}, and the depth of cut a_p = 1 mm. An image analysis of the size of the largest and smallest fraction was performed. Most of the chips generated during the face milling of poplar wood were classified as flat grain wood. A small percentage of the generated chips could be included in the group of rod-shaped fibrous bulk particles with a considerable extension in one direction (smaller fractions generated at a feed rate of 2.5 m·min^{-1}, and at the finest fractions- dust generated in all of the combinations of technical and technological parameters).

Keywords: Juvenile wood; Milling; Chip thickness; Cutting speed

*Contact information: a: Department of Machinery Control and Automation, Faculty of Environmental and Manufacturing Technology, Technical University in Zvolen, Študentská ulica 26, Zvolen, 960 53, Slovakia; b: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; *Corresponding author: gaffmilan@gmail.com*

INTRODUCTION

In the future, juvenile wood will be of increasing importance, and its workability will also increase, thanks to the technological development of sawmills and the rapidly developing new and improved aspects of wood processing. Juvenile wood occurs in the early years of tree growth; it is located near the pith and in the branches. In practice, it is very important to take into account the differences in juvenile wood. The authors expect that in the future the importance of juvenile wood will increase with the increasing amount of its processing. Not so long ago, juvenile wood was considered a poor quality material, but research has shown that juvenile wood is more appropriate in the production of certain products, such as medium-density fibreboard (MDF), oriented strand board (OSB), and bio-boards (Hejma 1981). Therefore, it is necessary to consider the size, shape, and amount of chips that the milling process creates. The chip properties depend on the physical and mechanical properties of the wood, and the technical and technological conditions of the milling process. Current scientific research does not provide information that would characterize the properties of juvenile wood chips. There is also no literature comparing juvenile and mature wood depending on specific technological conditions for wood splitting. This article addresses the issue of the size of poplar wood chips (*Populus tremula* L. and *Populus Euramericana* Serotina) generated by face milling. Both the juvenile and mature wood were analyzed. In the woodworking industry, the removal of chips from the place of their origin into a timber cutting machine is usually resolved with a vacuum system. In terms of environmental criteria, the vacuum system must be adapted to the changes in the milled material, and the changes in technical and technological conditions. Therefore, it is necessary to clarify and specify the characteristics of shredded wood arising under specific conditions.

Juvenile wood is defined as wood that is formed in the first few years of tree growth. The properties of wood on a young tree and wood on a mature tree near the pith in the treetop are different. The wood of a young and mature tree has a different annual ring structure. A different amount of spring and summer wood are in these annual rings (Zobel and Sprague 1998). This is reflected in the microscopic, submicroscopic, and chemical composition of this young wood. Naturally, it is reflected in the physical, mechanical, and other properties of the wood (Čunderlík 2002). In general, juvenile wood is defined as a specific number of annual rings around the pith, where there is a gradual change in the structure and properties of the wood. The older annual rings, or the part around the outer edge, are called older wood, outer wood, or mature wood. The proportion of juvenile wood changes depending on the tree species and between individual trees. It depends on many factors, most importantly the geographic location, soil quality, treetop size, habitat, and location of an individual tree in a plantation or the method of cultivation in a forest. In practical terms, it is important to know how much juvenile wood is among processed wood, or more precisely how much juvenile wood gets into semi-products or finished products after the first stage of processing (Požgaj *et al.* 1997).

The properties of juvenile wood do not change rapidly, but gradually; thus, there is no clear demarcation between the juvenile and mature wood. For this reason, it is impossible to accurately define the amount of juvenile wood in a section of the trunk. The largest percentage of juvenile wood in trees occurs approximately up to the twentieth annual ring. It comprises a substantial part of the volume of roundwood assortments with a smaller diameter from thinning, residual logs from the production of veneer, plantations of fast-growing tree species, and the top part of mature trees. The basic anatomical characteristics of juvenile wood differ from mature wood with shorter cells, a smaller cell diameter, thinner cells, higher proportion of libriform fibers, lower proportion of vessels, and a larger fibrillar angle (Maeglin 1987; Söğütlü 2010a). The juvenile wood of deciduous trees demonstrates lower physical properties, greater shrinkage, and low strength. There are greater differences between juvenile and mature wood among conifer wood species and ring-porous wood in comparison with diffuse-porous wood. Most diffuse-porous wood species produce juvenile wood that is only slightly different from the mature wood. This implies that there is a minimal impact on the production quality, which is why fast-growing species can be felled even in their early years when nearly all the wood is juvenile, without significant loss of quality. Most species of deciduous trees have a lower density near the pith than near the bark. The reduced density of diffuse-porous wood is variable, but the differences in the reduced density between juvenile and mature wood are generally very small, depending on the particular tree species. In addition to reduced density, the size of the vessels and fiber length also affects the quality of juvenile wood. The number of vessels per mm^2 is higher in juvenile wood than in mature wood, the total area is smaller and the vessels are narrower. The thickness of the cell wall increases from the center of the trunk to the bark (Zobel and Sprague 1998).

Milling is a machining process with a rotary tool (milling cutter, milling head, *etc.*), in which the depth of the cut changes the nominal chip thickness from the minimum value to the maximum value in counter-rotating milling, or from the minimum to the maximum value in simultaneous milling. The width or shape of the machined material also changes (Prokeš 1982; Hellström *et al.* 2008; Barcík and Gašparík 2014). Due to the rotational movement of the cutting wedge and the rectilinear motion of the workpiece, the resulting motion of the cutting wedge is cycloid (Peters *et al.* 2002; Hellström *et al.* 2009; Škaljić *et al.* 2009; Söğütlü 2010b). Because the ratio of the value of the cutting speed and feed rate is considerably high, the cycloid is extended to such an extent that it can be assumed with virtually no large error that the cutting path forms a circle (Buda *et al.* 1983; Lisičan *et al.* 1996; Novak *et al.* 2011) (Fig. 1). Based on the considerations mentioned above, the present study assessed the effect of technical, technological, and material factors that affect the size of juvenile poplar wood chips. Counter-milling was employed with combined cutting of longitudinal - front - tangential models.

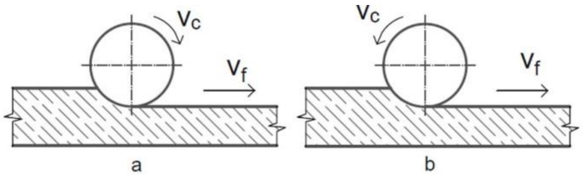


Fig. 1. Milling process by way of the feed panel: a) opposed milling and b) simultaneous milling

The dimensions of chips were measured in relation to the direction of the sample fibers and the cutting model - the plane milling machining. In the direction of the fibers, the width perpendicular to the fibers is lengthwise (the context with the thickness of the machined sample) the size of the chips and the thickness is evident in the context of the size of the stitch (1mm).

EXPERIMENTAL

Materials

Two types of poplar wood were used for specimens. The first samples were made from aspen poplar (*Populus tremula* 10 picies), which originated from the locality of Kováčovská valley near Zvolen, Slovakia. The determined age of the trees according to the annual rings was 45 years, and the proportion of juvenile wood in their trunk was determined to be approximately 27%. The trees were cut at 50 cm from the ground. Two 10-meter pieces were cut from the trunks, which were then divided into four 2.5-meter pieces. The second samples were cut from Euroamerican poplar (*Populus euroamericana* 10 pieces) Serotina. This is a hybrid of aspen poplar (*Populus tremula*) and I214 poplar (*Populus italica 214*). The grower determined the percentage of juvenile wood in the trunk to be 30%. Two 5.25-meter pieces were cut from the trunk, whereas one piece was from the lower part of the trunk and the other was cut from the central part of the trunk. These pieces were shortened to 2.5 m, and then they were cut with a frame saw symmetrically to the pith. The prepared lumber was then dried and acclimatized at 12% moisture content.

Radial boards were cut from the pieces, which contained the highest percentage of juvenile wood. These boards were then cut radially through the pith, and the part with the bark was also removed, after which the boards were cut to a length of one meter. The prepared boards were then dried and acclimatized at a relative air humidity φ = 65% and temperature t = 20 °C to 12% moisture content. After the required parameters were achieved, the boards were cut and leveled to 35-mm thickness, which mean that was tested samples with dimensions (L/R/T), (1000/ 35/35). This operation prepared the samples for the experimental process, where the part near the pith contained the juvenile wood and the part near the bark contained mature wood. The specimens were radial (center) lumbers pieces, on which it is realistic to see the difference between the juvenile and mature wood (in the width of the annual circles) its mean transition zone (7-10 annual rings).

Methods

The physical properties were used to determine the density in an absolutely dry state and the reduced density. The dimensions of the specimens for determining the density were 30 mm length along the grain, 20 mm width, and 20 mm thickness. The samples were prepared in a way that enabled the authors to determine the density throughout the cross-section of the trunk. It was necessary to bring the moisture content of the samples down to w = 0%; on the basis of this requirement, they were oven-dried at 103 °C ± 2 °C, until the weight of the two consecutive measurements did not differ by ±2 g. To avoid the adsorption of moisture and an increase in weight and volume, the dried specimens were placed in a glass container with silica gel, where they remained throughout the measurement process. The specimens were weighed and measured, and these dimensions were used to calculate the density in a completely dry state and the reduced density.

The mechanical properties selected affect the interaction between the tool and the workpiece during milling, in which the wood chips were obtained and examined. The bend and impact resistance were selected as the most appropriate characteristics. The authors examined the properties of specimens that were acclimatized to a final humidity of 12% in a climatic chamber at t = 20 °C and φ = 65%, where the humidity was measured by the gravimetric method, using laboratory HLD (HLD, Prague) weighing instruments with a precision of 0.005g.

The flexural strength was examined in the tangential direction. The specimens were acclimatized to 12%, the dimensions of the specimens were as follows: width 20 mm in the radial direction, thickness 20 mm in the tangential direction, and the length was 450 mm along the grain. The flexural strength test was performed on the TIRATEST 2200 machine (TIRA, Schalkau, Germany). The support span was 400 mm, and the applied load force was in the tangential direction. The samples were bent at the middle lengthwise (Fig. 2) using a universal testing machine FPZ 100 (TIRA, Schalkau, Germany) in accordance with ISO 13061-3 (2014).

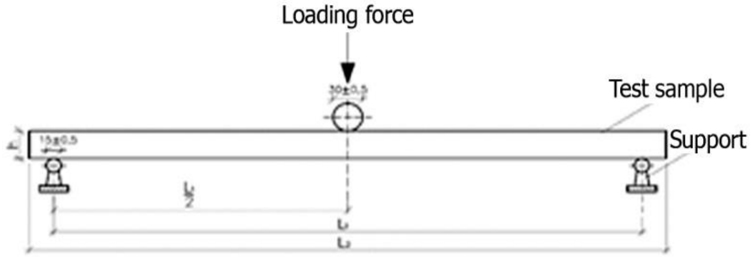


Fig. 2. Principle of the three-point bending test according to ISO 13061-3 (2014)

The impact strength was also measured in the tangential direction. The dimensions of the specimens were as follows: width 20 mm in the radial direction, thickness 20 mm in the tangential direction, and the length was 250 mm along the grain. The specimens were also acclimatized to 12% humidity. The test was performed using the Charpy hammer (hammer weight 20-kg), using a universal testing machine FPZ 100 (TIRA, Schalkau, Germany). The spread of supports on the Charpy hammer was 240 mm. The IBS “Impact bending strength” (Fig. 3) test was calculated in accordance with ISO 3348 (1975) and Eq. 1,

$$A_w = \frac{Q}{b * h} \tag{1}$$

where A_W is the IBS of wood (J.cm^{-2}), Q is the energy involved in damaging the test specimen (J), b is the width of the sample (cm), and h is the height (thickness) of the sample (cm).

The IBS values were converted to the moisture content of 12% in accordance with ISO 3348 (1975) and Eq. 2,

$$A_{12} = A_w[1 + \alpha(w - 12)] \tag{2}$$

where A_W is the wood bending strength at the moisture during testing (MPa), A_{12} is the wood bending strength at the moisture of 12% (MPa), w is the sample moisture during testing (%), and α is the moisture correction coefficient, which was taken to be equal to 0.04 for all wood species.

Charpy’s principle can be briefly described as follows: A hammer falls along a circular trajectory from height h_1; if the hammer has no obstacle, it reaches height h_0; it applies $h_0 < h_1$ because of friction resistance; if the hammer hits the experimental sample, it also reaches the left side but only to the position h_2; the work necessary for breaking the sample is recorded on the apparatus’ dial (Fig. 3).

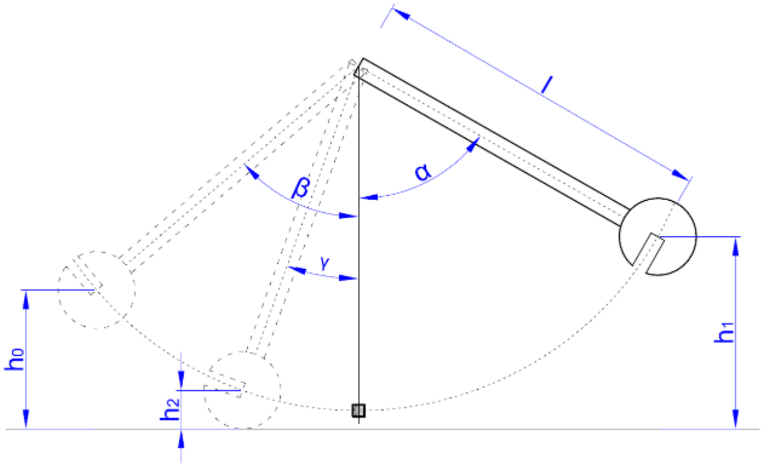


Fig. 3. Principle of the impact bending strength test according to EN 310 (1993)

Milling

The milling was performed in an experimental device on a bottom side machine FVS (Ligmet, Hradec Králové, Czech Republic) (Fig. 4), and the feed of the material was secured with a Frommia feeding device with a gradually increasing feed rate. The technical parameters are shown in Table 1.

Table 1. Technical Parameters

Bottom side Machine FVS		**Feeding Device Frommia**	
Supply Systems	360/220 (V)	**Type**	ZMD 252 / 137
Frequency	50 (Hz)	**Feed Range**	2,5; 10; 15; 20; 30 (m·min^{-1})
Power Input	4 (kW)	**Engine**	380 (V) / 2 800 (m/min)
Production Year	1976	**Production Year**	1972
Manufacturer	Ligmet Hradec Králové	**Manufacturer**	Maschinenfabrik Ferdinand Fromm

Fig. 4. Bottom side machine with feeding device

In the experimental measurements, the cutting tool used was the harvesting head for wood FH 45 Staton (SZT, Turany, Slovakia) with replaceable blades, with the parameters shown in Table 2 and Fig. 5.

Table 2. Cutting Tool Parameters

Diameter of the milling head body	125 (mm)
Diameter of the milling head body with extended blade	130 (mm)
Thickness of the milling head body	45 (mm)
Number of blades	2
Tooth geometry	α = 30°, β = 45°, γ = 15°

Legend: α - Clearance angle, β - Wedge angle, γ - Rake angle

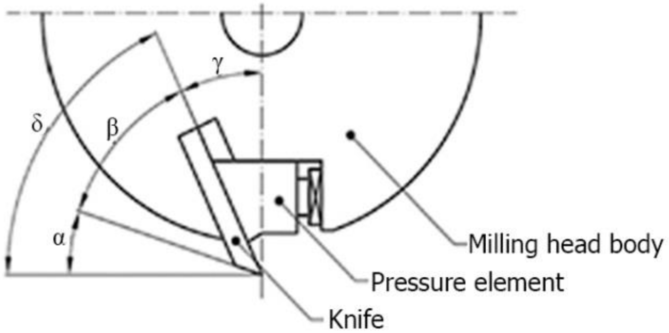


Fig. 5. Geometry of the milling head

The samples intended for the experiment were counter-milled under different conditions, which are listed in Table 3. During the milling a sample of approximately 200 g of chips was taken for dimensional analysis, for each combination of cutting conditions separately. After the chips were removed, the device was cleared of residual debris and prepared for a new collection of samples.

Table 3. Cutting Parameters

Feed Speed v_f (m·min^{-1})	2,5
	15
Rotating Speed n (min^{-1})	4450
	6670
	8900
Cutting Speed v_c (m·s^{-1})	30
	45
	60
Removal Depth a_p (mm)	1

Dimensional analysis

In the dimensional analysis, a largest fraction of 8 mm and a smallest fraction under 1 mm was monitored. The samples for monitoring the dimensions of wood chips were obtained from a granulometric (sieve) analysis, *i.e.* after the evaluation samples of the largest and smallest fraction were prepared. All chip samples (24 samples for the largest fraction and 24 samples for the smallest fraction) were recorded with a CCD Mitsubishi (Tokio, Japan) camera at 10-fold magnification. During the analysis of the largest fraction, 30 particles for each sample were evaluated, and approximately 1,000 particles were evaluated in the smallest fraction. The program Lucia G/Comet version 3.52a (Laboratory Imagining, Praha, Czech Republic) was used to create an image analysis of the dimensions (length and width) in each frame. The measured data were used to calculate average values. The process of measuring the dimensions of individual images in Lucia G/Comet 3.52a: 1) Creation of image; 2) Saving of image; and 3) Creation of a macro for measuring the dimensions of individual objects in the image, which consists of the following operations: opening the file with the image and selecting it, cutting it at a certain level, filling out objects in the image, separating objects in the image (for the smallest fraction), measuring objects in the image, measuring the dimensions with the created macro, and saving the measured data.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

Table 4 shows the measured values of the physical and mechanical properties. The average density of aspen poplar in an absolutely dry state was 368 kg·m^{-3}, the lowest density measured in the pith was 329 kg·m^{-3}, and the maximum density value measured in the cambium was 428 kg·m^{-3}. The density from the pith to the bark increased by up to 26.5%. On the borderline between juvenile and mature wood (selected tenth annual ring), the average density of the juvenile wood was 349 kg·m^{-3}, and the average density of the mature wood was 380 kg·m^{-3}.

Table 4. Measured Values for Physical and Mechanical Properties

		Populus tremula	Poplar Serotina
Average Density Value	Juvenile Wood (kg·m^{-3})	**349** (5.4)	**313** (5.6)
	Mature Wood (kg·m^{-3})	**380** (6.2)	**343** (6.7)
	Total (kg·m^{-3})	**368** (4.8)	**334** (5.0)
Average Value of Breaking Strength	Juvenile Wood (MPa)	60.48 (11.7)	46.11 (9.7)
	Mature Wood (MPa)	66.59 (10.6)	51.8 (12.4)
	Total (MPa)	64 (9.8)	50 (15.4)
Average Value of Modulus of Elasticity	Juvenile Wood (MPa)	6874 (12.2)	5648 (10.2)
	Mature Wood (MPa)	7979 (11.6)	7023 (13.4)
	Total (MPa)	7519 (10.8)	6602 (15.3)
Average Value of Impact Strength	Juvenile Wood (J/cm^2)	1.97 (10.1)	2.81 (12.3)
	Mature Wood (J/cm^2)	3.28 (9.9)	5.10 (11.6)
	Total (J/cm^2)	2.78 (12.5)	4.45 (10.7)

Values in parentheses are coefficients of variation (CV) in %

In the Serotina poplar, the highest density values were measured near the bark, and the lowest density values were measured near the pith, as was the case with aspen poplar. The lowest density value for Serotina poplar was 302 kg·m^{-3}, and the maximum density value was 382 kg·m^{-3}. The density from the pith to the bark increased in the range of 26%. On the borderline between juvenile and mature wood (selected tenth annual ring), the average density of the juvenile wood was 313 kg·m^{-3}, and the average density of the mature wood was 343 kg·m^{-3}. The total average density of the trunk was 334 kg·m^{-3}. It was determined that mature wood had 9% higher density than juvenile wood in the given wood species.

The average yield strength of the examined aspen poplar was 64 MPa, and the modulus of elasticity was 7519 MPa; there was no distinction between the juvenile and mature wood in the examined poplar yet. In this measurement, there was also an increase in the values of the yield strength and modulus of elasticity from the pith to the bark; the increase in the yield strength was 32%, ranging from 56 MPa to 74 MPa. The modulus of elasticity increased by up to 45%, the lowest value was 6199 MPa, and the highest value was 8969 MPa. The average yield strength of juvenile wood was 60 MPa and the average yield strength of mature wood was 66 MPa, which was 10% higher. The difference in the modulus of elasticity between juvenile and mature wood was 16%, where the juvenile wood had a value of 6874 MPa, and mature wood had a value of 7979 MPa. The strength properties were affected by the reaction wood that occurred in poplar wood species, where a slight deformation on one side showed that the strength properties on one side of the trunk reached higher values than on the other side of the trunk. Therefore, the average value of the yield strength on the right side of the pith was 64 MPa, and on the left side it was 7% higher, specifically 69 MPa.

The Serotina poplar had a yield strength of 50 MPa and a modulus of elasticity of 6602 MPa. There was also an increase in values from the pith to the bark, with a yield strength that ranged from 36 MPa to 66 MPa, which was an overall increase of 45%. The lowest value of the modulus of elasticity was 5086 MPa, and the highest value was 8583 MPa, which represented an increase of 45%. The yield strength of juvenile wood was 46.11 MPa, and the yield strength of mature wood was 51.8 MPa, which was a 12% difference.

The strength properties of juvenile wood were lower than those of mature wood; the modulus of elasticity of juvenile wood was 5648 MPa, and the modulus of elasticity of mature wood was 7023 MPa. The difference between the values was 24%.

The average impact strength was 2.78 J.cm^{-2}, where the lowest value found near the pith was 1.3 J.cm^{-2}, and the highest value found near the bark was 4.69 J.cm^{-2}. The average value in juvenile wood was 66 % lower (1.97 J.cm^{-2}) than in mature wood (3.28 J. cm^{-2}). In this measurement, the occurrence of reaction wood was also taken into account, which resulted in a slight deformation in the impact strength profile. In Serotina poplar the average impact strength value throughout the trunk was 4.45 J.cm^{-2}, where the lowest value near the pith was 1.37 J.cm^{-2}, and the highest value near the bark was 7.54 J.cm^{-2}. In juvenile wood the average impact strength value was 2.81 J.cm^{-2}, and the average value in mature wood was 5.1 J.cm^{-2}. This meant that it was up to 81% higher, which was due to the high proportion of lignin in the juvenile wood and resulted in fragility.

Dimensional Analysis

Table 5. The Basic Dimensions of the Largest Chip Fractions above 8 mm for Aspen Poplar.

v_c=30 m·s^{-1}, v_f= 2.5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=30 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	26.8	1.2	28.9	0.5	**Avg. value**	24.2	1	27.2	1
Min. value	9	0.5	15.5	0.3	**Min. value**	13.2	0.6	18	0.5
Max. value	38.7	1.7	40	1.2	**Max. value**	32.6	1.3	35.4	1.4
v_c=45 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=45 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	35.7	1.3	40.6	1	**Avg. value**	24	1.8	30.8	1.1
Min. value	14.6	0.9	31.8	0.7	**Min. value**	12.7	1	17.5	0.5
Max. value	51.4	1.8	48.3	1.3	**Max. value**	37.4	2.6	42.7	1.6
v_c=60 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=60 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	34	1.1	37.8	1.5	**Avg. value**	29.6	1.1	28.8	0.7
Min. value	26.3	0.7	23.4	0.4	**Min. value**	18.7	0.5	16	0.5
Max. value	45.7	1.5	54.7	0.8	**Max. value**	46.5	1.6	41.7	1

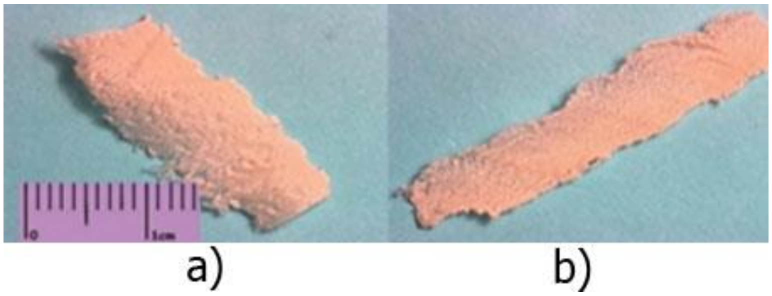
Dimensions are in millimeters.

A dimensional analysis of the particles (chips) determined the basic dimensions of the largest particles of the coarse fraction chips with dimensions over 8 mm, and the dimensions of the smallest fraction particles with dimensions under 1 mm, specifically the length and width of the chips. The basic dimensions of poplar chips generated under the given technical and technological conditions are listed in Tables 5 through 8.

Table 6. The Basic Dimensions of the Largest Chip Fraction above 8 mm for the Poplar Serotina Clone.

v_c=30 m·s^{-1}, v_f= 2.5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=30 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	24	1.2	36	1	**Avg. value**	23.2	0.9	26	0.9
Min. value	10.9	0.9	27.5	0.6	**Min. value**	12	0.5	12.3	0.5
Max. value	33.3	1.9	47.9	1.5	**Max. value**	45.5	1.5	46.1	1.2
v_c=45 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=45 m·s^{-1} , v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	27	1	39.4	0.4	**Avg. value**	20.6	1.2	26.3	1.1
Min. value	14.5	0.9	9.8	0.2	**Min. value**	10	0.7	11.5	0.6
Max. value	42.2	1.2	76.6	0.8	**Max. value**	28	1.9	42.5	1.4
v_c=60 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=60 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. value	30.3	0.9	38.4	0.6	**Avg. value**	27	0.9	32.3	1
Min. value	14.6	0.6	22.7	0.3	**Min. value**	11.8	0.6	12.6	0.8
Max. value	58.2	1.1	55.8	1	**Max. value**	38.8	1.4	57.9	1.5

Dimensions are in millimeters.



a) b)

Fig. 6. The largest fraction of aspen poplar at v_f =2.5 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

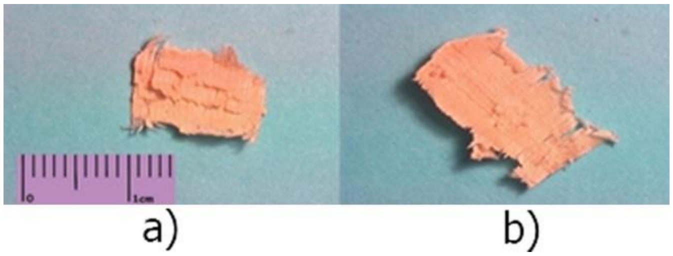

a) b)

Fig. 7. The largest fraction of aspen poplar at v_f =15 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

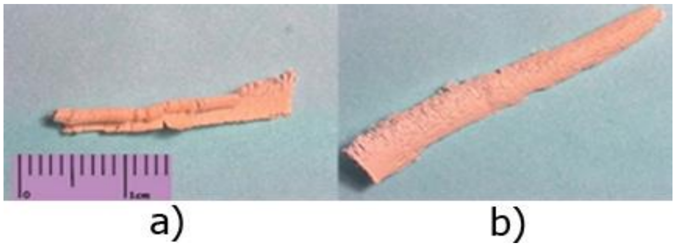

a) b)

Fig. 8. The largest fraction of the poplar clone at v_f =2.5 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

Table 7. The Basic Dimensions of the Smallest Chip Fraction under 1 mm for Aspen Poplar, Values Given in µm

v_c =30 m·s^{-1}, v_f= 2.5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=30 m·s^{-1} , v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	363	154	238	100	**Avg. Value**	307	122	239	101
Min. Value	30	40	30	41	**Min. Value**	30	40	30	40
Max. Value	1097	1057	1089	895	**Max. Value**	1084	876	1096	746
v_c=45 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=45 m·s^{-1} , v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	332	134	206	105	**Avg. Value**	288	104	235	98
Min. Value	30	45	30	42	**Min. Value**	30	39	30	40
Max. Value	1096	1050	1081	736	**Max. Value**	1099	842	1098	716
v_c=60 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=60 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	131	114	204	99	**Avg. Value**	238	89	217	131
Min. Value	30	40	30	40	**Min. Value**	30	40	30	40
Max. Value	1073	789	1094	649	**Max. Value**	1095	762	1094	875

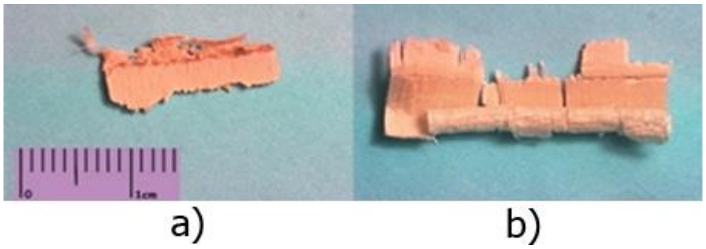


Fig. 9. The largest fraction of the poplar clone at v_f =15 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

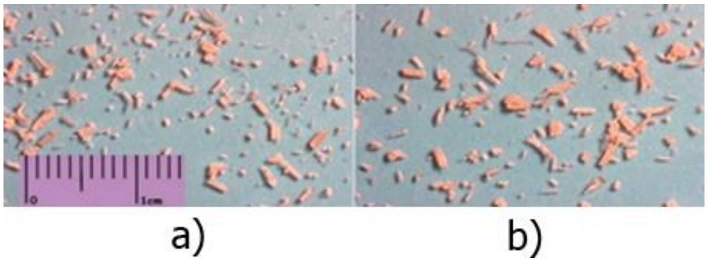


Fig. 10. The smallest fraction of both poplars at v_f =2.5 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

Table 8. The Basic Dimensions of the Smallest Chip Fraction under 1 mm for the Poplar Serotina Clone

v_c=30 m·s^{-1}, v_f= 2.5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=30 m·s^{-1} , v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	232	113	224	116	**Avg. Value**	323	152	220	110
Min. Value	30	40	30	38	**Min. Value**	30	43	30	40
Max. Value	1094	582	1083	642	**Max. Value**	197	893	1077	655
v_c=45 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=45 m·s^{-1} , v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	224	100	210	87	**Avg. Value**	298	154	199	90
Min. Value	30	43	30	40	**Min. Value**	30	45	30	38
Max. Value	1068	658	1096	495	**Max. Value**	1096	682	1062	705
v_c=60 m·s^{-1}, v_f= 2,5 m·min^{-1}	Juvenile Wood		Mature Wood		**v_c=60 m·s^{-1}, v_f= 15 m·min^{-1}**	Juvenile Wood		Mature Wood	
	Particle Length	Particle Width	Particle Length	Particle Width		Particle Length	Particle Width	Particle Length	Particle Width
Avg. Value	197	95	210	81	**Avg. Value**	225	118	196	84
Min. Value	30	38	30	40	**Min. Value**	30	42	30	40
Max. Value	1094	367	1098	422	**Max. Value**	1081	754	1097	619

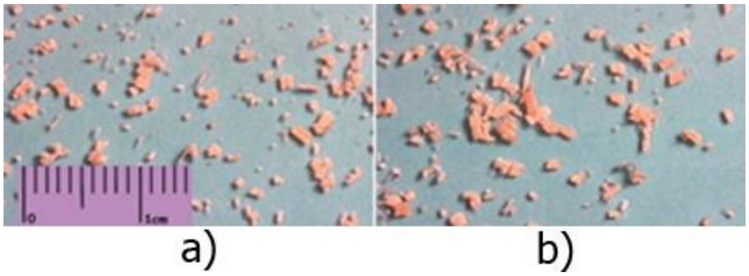


Fig. 11. The smallest fraction of both poplars at v_f = 15 m.min^{-1} and v_c = 30 m.s^{-1} for a) juvenile wood and b) mature wood

The results of the dimensional analysis of the individual particles show that milled lumber created through the process of face milling of poplar wood could be classified as flat grain wood. In flat grain wood, the length and the width was substantially greater than the third dimension, *i.e.* the chip thickness (Figs. 7 through 10). Most of the generated chips were in this group. A small percentage of the generated chips could be included in the group of rod-shaped fibrous bulk particles with a significant extension in one direction-smaller fractions generated at a feed rate of 2.5 m·min^{-1}, and the finest fractions (dust) generated at all of the cutting parameters. The average measured length of 8 mm fraction particles ranged from 20.6 mm to 35.7 mm, and the width ranged from 0.4 mm to 1.8 mm. The average measured length of the fraction particles under 1 mm ranged from 196 mm μm to 356 mm μm, and the width ranged from 81 μm to 154 μm.

The Effect of the Feed Rate and Cutting Speed

The effect of the feed rate on the chip dimension was clear. Increasing the feed rate during milling generated shorter chips. At 8 mm fraction, the chips were 3% to 33% shorter at 15 m.min^{-1} than at 2.5 m·min^{-1}. However, there was no clear effect of the feed rate on the width of the chips at maximum fraction. At the smallest fraction, no dependence between the chip dimensions and the feed rate was found. The effect of the feed rate on the chip dimensions was similar to the effect of the feed rate on the granulometric analysis, *i.e.* it was also based on the kinematics of the cutting process.

The dependence of the dimensions of the largest fraction on the cutting speed was not as clear as their dependence on the feed rate. In most cases, as the cutting speed increased (a combination of technical and technological parameters), the dimensions of the largest chip fraction increased, and in a few cases the chip dimensions decreased. Changing the cutting speed from 30 m·s^{-1} to 45 m·s^{-1} changed the length and width of the largest chip fraction, namely the length increased by 1% to 40%, and the width increased by 8% to 100%. When the cutting speed was changed from 45 m·s^{-1} to 60 m·s^{-1} the length and width of the largest chip fraction changed, namely the length increased by 3% to 30%, and the width increased by 10% to 65%. In the case of the smallest fractions, the dimensions decreased as the cutting speed increased. When the cutting speed was changed from 45 m·s^{-1} to 60 m·s^{-1} the length was reduced by 2% to 14% and the width by 3% to 25%, and changing the speed from 45 m·s^{-1} to 60 m·s^{-1} reduced the length by 0% to 24% and the width by 5% to 23%. The theoretical effect of the cutting speed on the chip size was based on the kinematics of the cutting process, similar to the feed rate, which meant that the type of chip generated depended on the duration of the contact between the cutting tool and the workpiece. However, the theoretical effect of the cutting speed on the chip dimension was not confirmed.

The Effect of the Wood Type on the Chip Dimension

An evaluation of the largest 8 mm fraction showed that chips from juvenile wood were 7% to 33% shorter and 9% to 150% percent wider. At the smallest fraction, juvenile wood chips were 6% to 24% wider and 4% to 38% longer. No noticeable effect of the different properties of juvenile wood was demonstrated in the smallest fraction. The chips generated during the milling of juvenile wood were shorter and wider in comparison to the mature wood. This was due to the lower hardness and higher fragility of the wood. These characteristics were due to the different anatomical and chemical structure of the wood.

The Effect of the Wood Species on Chip Dimension

Based on the comparison of different types of poplar, it can be concluded that the milling of aspen poplar generated chips that were 10% to 32% longer and 11% to 50% wider than those generated during the milling of Serotina poplar, particularly in the case of juvenile wood. This meant that Serotina poplar clones contained more juvenile wood, which affected the formation of the chips. The resulting dimensions of chips from mature wood were comparable in both types of wood species. There was no noticeable difference between the dimensions of the different poplar species at the smallest fraction under 1 mm.

CONCLUSIONS

1. The authors could classify most of the chips generated during the face milling of poplar wood as flat grain wood, in which the length and width was substantially greater than the third dimension, *i.e.* chip thickness. A small percentage of the generated chips could be included in the group of rod-shaped fibrous bulk particles with a considerable extension in one direction (smaller fractions generated at a feed rate of 2.5 $m \cdot min^{-1}$, and at the finest fractions- dust generated in all of the combinations of technical and technological parameters).
2. Increasing the feed rate during milling generated shorter chips. When the feed rate was changed it did not change the width of wood chips at the largest fraction. The effect of the cutting speed on the chip dimension was not confirmed.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Internal Grant Agency of the Faculty of Environmental and Manufacturing Technology project No. 3/2016, “Impact of selected technological, tool and material factors on the surface finish of plane milling Thermomodified oak wood”, VEGA 1/0315/17, “Research of relevant properties of thermally modified wood at contact effects in the machining process with the prediction of obtaining an optimal surface”, VEGA 1/0725/16, “Prediction of the quality of the generated surface during milling solid wood by razor endmills using CNC milling machines” and the University Internal Grant Agency (CIGA) of the Faculty of Forestry and Wood Sciences, project No. 2016-4309.

REFERENCES CITED

Barcík, Š., and Gašparík, M. (2014). "Effect of tool and milling parameters on the size distribution of splinters of planed native and thermally modified beech wood," *BioResources* 9(1), 1346-1360. DOI: 10.15376/biores.9.1.1346-1360

Buda, J., Souček, J., and Vasilko, K. (1983) *Teória obrabánia* [Theory of machining], State Publishing House of Technical Literature, Prague, Czech Republic, pp. 355-382, +386.

Čunderlík, I. (2002). "Juvenilné drevo," in: *Trieskové a Beztrieskové Obrábanie Dreva´02*, Vydavateľstvo TU vo Zvolene, Zvolen, Slovakia, pp. 77-83.

ISO 13061-3 (2014). "Physical and mechanical properties of wood -- Test methods for small clear wood specimens -- Part 3: Determination of ultimate strength in static bending," International Organization for Standardization, Geneva, Switzerland.

Hejma, J. a kol. (1981). *Vzduchotechnika v dřevozpracovávajícím průmyslu* [Ventilation in the wood processing industry], SNTL– Nakladatelství technické literatury, Praha, Czech Republic (in Czech), pp. 34-36.

Hellström, L. M., Gradin P. A., and Carlberg, T. (2008). "A method for experimental investigation of the wood chipping process," *Nordic Pulp Paper Res. J.* 23(3), 339-342.

Hellström, L. M., Isaksson, P., Gradin, P. A., and Eriksson, K. (2009). "An analytical and numerical study of some aspects of the wood chipping process," *Nordic Pulp Paper Res. J.* 24(2), 225-230.

ISO 3310-1 (2007). "Test sieves. Technical requirements for testing. Part II: Test sieves of metal wire cloth," International Organization for Standardization, Geneva, Switzerland.

ISO 3348 (1975). "Wood-determination of impact bending strength," International Organization for Standardization, Geneva, Switzerland.

Lisičan, J. (1996). *Teória a Technika Spracovania Dreva* [*Theory and Technique of Wood Processing*], Matcentrum, Zvolen, Slovakia (in Slovak).

Maeglin, R. R. (1987). "Juvenile wood, tension wood, and growth stress effects on processing hardwoods," *Hardwood Research Council* 15(1), 100-108.

Novák, V., Rousek, M., and Kopecký, Z. (2011). "Assessment of wood surface quality obtained during high speed milling by use of non-contact method," *Drvna Industrija* 62(2), 103-115. DOI: 10.5552/drind.2011.1027

Peters, J. J., Bender, D. A., Wolcott, M. P., and Johnson, J. D. (2002). "Selected properties of hybrid poplar clear wood and composite panels," *Forest Products Journal* 52(5), 45-54.

Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva* [*Structure and Properties of Wood*], Príroda a. s., Bratislava, Slovakia (in Slovak).

Prokeš, S. (1982). *Obrábění Dřeva a Nových Hmot ze Dřeva* [*Woodworking and New Materials from Wood*], SNTL- Nakladatelství technické literatury, Prague, Czech Republic (in Czech).

Škaljić, N., Beljo-Lučić, R., Čavlović, A., and Obućina, M. (2009). "Effect of feed speed and wood species on roughness of machined surface," *Drvna Industrija* 60(4) 229-234. DOI: 10.1007/s10086-004-0655-x

Söğütlü, C. (2010a). "The effect of the feeding direction and feeding speed of planing on the surface roughness of oriental beech and Scotch pine woods," *Wood Research* 55(4), 67-77.

Söğütlü, C. (2010b). "The effect of some factors on surface roughness at planing process of cedar wood," *Gazi University*, *Journal of Polytechnic* 13(3), 177-181.

Zobel, B. J., and Sprague, J. R. (1998). *Juvenile Wood in Forest Trees*, Springer-Verlag, Berlin Heidelberg.

Article submitted: February 1, 2017; Peer review completed: May 2, 2017; Revised version received and accepted: May 15, 2017; Published: May 19, 2017.
DOI: 10.15376/biores.12.3.