

## Tool Wear Evolution and Surface Formation in Milling Various Wood Species

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This study presents the results of tool wear and surface roughness of wood processed by plain milling. The tests were done on wood samples of pine and black alder grown in Lithuania in order to clarify time-related tool blunting and the aspects of surface formation. The samples were milled along the fiber in the experimental wood cutting stand at two different cutting and feed speeds. The roughness parameter ( $R_z$ ) of the processed samples was measured in five sectors along and across the fiber using a contact profilometer. Registered values were analyzed by a Gaussian digital filter and evaluated according to relevant statistics seeking to minimize influence of wood anatomy. The obtained results helped to determine distinctions and variations of surface roughness, which strongly depend on the cutting path, rounding radius of the tool's cutting edge, cutting, and feed speeds while milling pine and black alder.

*Keywords:* Wood milling; Tool wear; Surface roughness; Pine wood; Black alder wood

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### INTRODUCTION

One of the main criteria to evaluate the quality of a processed surface is its roughness. It determines the further processing and finishing of the surface, appearance, and usage possibilities (Richter *et al.* 1995; Follrich *et al.* 2010; Ozcan *et al.* 2012; Kuljich *et al.* 2013; Pelit *et al.* 2015). Wood surface assessment is highly subjective from the scientific, technological, or product exploitation points of view; nevertheless, research-based quantitative and qualitative surface texture estimation has been carried out over various aspects of surface formation in wood milling. Distinction between anatomic and processing unevenness, which vary greatly for different wood physical properties, grain angle, and tool nose conditions, remains problematic (Kilic *et al.* 2007; Malkocoglu 2007; Aslan *et al.* 2008; Magoss 2008; Kilic 2015).

Wood milling process testing, modeling, and simulation in the works of different authors remain classic and pragmatic, showing that the following main factors affect the surface roughness the most: species of wood, mode of surface milling, the rounding radius ( $r$ ) of the cutting edge, cutting  $v_c$ , and feed  $v_f$  speeds (Malkocoglu 2007, Usta *et al.* 2007; Hernández and Cool 2008; Škalić *et al.* 2009; Novák *et al.* 2011; Hernández *et al.* 2014; Gaff *et al.* 2015; Ghosh *et al.* 2015; Kvietkova *et al.* 2015).

Wood is an anisotropic biocomposite (Niska and Sain 2008; Stokke *et al.* 2014). The wooden cells that participate in forming the anatomic unevenness of the wood surface are cut or deformed during mechanical processing (Goli *et al.* 2001; Magoss 2008). When the machining of the wood is analyzed, the anatomic unevenness of the surface usually has

not been taken into account, because in milling it is usually considerably of lower importance compared with the mechanical factors.

The classical wood cutting theory states that the surface roughness increases with the wear of the cutting tool (Magoss 2008). The main cause of the tool wear is considered to be the mode in which the tool nose and front friction interact with the wood (Beer *et al.* 2003, 2005; Beer 2005). Therefore, changes in the form of the cutting edge mainly depend on the angular and micro-geometrical parameters (Porankiewicz 2006; Kowaluk *et al.* 2009; Azemović *et al.* 2014) or technical characteristics of tools (Bendikiene and Keturakis 2017).

A number of related studies in the literature indicate the significance of feeding conditions in the milling of wood material (Sogutlu 2010). The feeding or cutting speed has an impact on the wood surface roughness (Sogutlu *et al.* 2016). In other words, surface roughness increases as feed rate is increased in the milling process (Sogutlu 2017).

Wood cutting theories give various models of chip and surface formation. For milling processes, the following algorithm related to tool wear evolution explains the cutting phenomenon (Csanády and Magoss 2013): when the wood is milled with a sharp tool ( $r < 20 \mu\text{m}$ ), the beginning of the cutting process is considered to be concentrated at the contact of the cutting edge with the minimal contact stress matrix to the wood (Keturakis and Juodeikiene 2007). The cutting edge of the tool cuts the wooden fibers and forms continuous chips or shavings of the regular form. The quality of the processed surface is of the highest quality and the defects are caused by the unfavorable direction of wooden fibers, or microcrushing at the top of the cutting edge (Su *et al.* 2002, 2003).

When milling is performed using a dull tool ( $20 < r < 40 \mu\text{m}$ ), the undesirable process of the tool nose bottom sliding on the wooden surface appears (Keturakis and Juodeikiene 2007). During the sliding period the tool's cutting edge slides along the surface of the wood and deforms and compresses it. Under the influence of the viscous-elastic deformation, the wooden surface absorbs the compressing effect of the tool's cutting edge. However, the plastic and residual deformations cause the formation of a resilient wooden layer in front of the tool that rolls as the wave. When the tensions of this surface layer reach a critical limit, the fiber disruption process starts. When the fibers are cracked and up-lifted, the tool's cutting nose effectively reaches the wood. This is the end of the sliding process and beginning of chip cutting. The quality of the processed surface is substantially worse compared with the sharp tool; separate splits and rougher stress-recovery segments appear (Goli *et al.* 2001; Magoss and Sitkei 2001).

When milling is done with a blunt tool ( $r > 40 \mu\text{m}$ ), the irregular cutting process takes place (Keturakis and Juodeikiene 2007). The blade forms the surface not directly and primarily by the tool nose cutting, but mostly through deep stress penetration, fiber compression, and disruption. Due to the resilient changes of the sliding period, the place of slippage through the fibers extends much more and remotely forward from the cutting nose contact zone. This is the reason why the uncontrolled chip splits along the grain appear, causing noticeably rougher surface parts. The resilient density related stress recovery of the machined wood surface up to 0.2 mm or even more start. The processed surface does not satisfy the acceptable quality criteria (Magoss and Sitkei 2001).

A similar model might be applied to the milling kinematics. When the feed per cutter  $f_z$  grows from 0.5 mm to 3.0 mm, the kinematic (processing) unevenness appears, and the quality of the surface decreases (Magoss and Sitkei 2001). The waviness of the surface is attributed to the kinematic unevenness. It is formed by the rotating movement of the milling tool. The surface waviness is described by the length and depth of the wave. It

is possible to calculate and predict these parameters. The size of the kinematic unevenness depends on the number of the cutters taking part in the cutting process, cutting radius, feed per cutter, and cutting speed, but the grain direction is essential. The most optimal cutting regime and the best quality of the surface are achieved when the feed per cutter  $f_z$  is from 1.0 mm to 2.0 mm (Brown and Parkin 1999; Magoss and Sitkei 2001; Jackson *et al.* 2002; Hynek *et al.* 2004).

When the cutting speed increases, the quality of the surface normally improves. For flat cylindrical milling of the wood planes, the recommended cutting speed is from 35 m/s to 55 m/s. In this range of the cutting speed, the best quality of the surface and the lower numeric values of the cutting forces are achieved. When the cutting speed is further increased ( $v_c > 60$  m/s), the cutting force increases, and the vibration of the cutting tool becomes more active. The tool's vibration creates additional unevenness that decreases the quality of the processed surface (Magoss 2008; Gaff *et al.* 2015; Kvietskova *et al.* 2015).

The angle of fiber direction primarily affects the quality of the surface. The surface roughness decreases with the increase of the angle between the fiber direction and the vector of cutter feed speed. However, when a moderately blunt tool is used, the surface roughness decreases with the increase of the angle of fiber direction up to 30°, and then it starts to grow again. When tests with the blunt cutter were done, the opposite effect was noticed, *i.e.*, the roughness increases when the fiber angle changes from 30° to 40° (Goli *et al.* 2010).

While examining milled surface quality of thermally modified and not modified *Pinus sylvestris* L. (Pinkowski *et al.* 2016) it was ascertained that the higher feed speed (5 m/min) led to increase of surface roughness parameters and reduction of surface quality; thermally modified pine wood showed lower surface roughness. Very similar results were achieved with birch wood (*Betula pendula* L.) – increases in cutting speed reduced the average roughness, while increases in feed speed had the opposite effect (Kvietskova *et al.* 2015). The highest roughness was achieved after plane milling with a feed speed of 11 m/min.

Modern wood milling studies provide more and more knowledge on tool interactions with wood and subsequent surface formation. The objective of present study was to determine the influence of the cutting path and rounding radius of the cutting edge on the surface roughness, when the wood samples of pine and black alder is milled along the fiber at different cutting and feeding speeds. Special attention was given to the phenomenon emerging during transition from the initial and highly dynamic tool nose wear towards more stable and monotonic abrasion.

## EXPERIMENTAL

The testing samples were made from the wood of pine and black alder grown in Lithuania (Table 1).

**Table 1.** Physical Characteristics of Wood

Wood Species	Moisture Content $\omega$ (%)	Number of Annual Rings per 1 cm	Average Width of Annual Ring (mm)	Average Density (kg / m <sup>3</sup> )
Pine ( <i>Pinus sylvestris</i> L.)	10.9	4.21	2.37	504
Black alder ( <i>Alnus glutinosa</i> L.)	9.4	3.92	2.55	457

A total of 60 samples were prepared with a length of 1000 mm, width of 100 mm, and thickness of 45 mm. The average temperature in the testing room was  $t = 18 \pm 2$  °C, and relative air humidity was  $\varphi = 60 \pm 5\%$ .

The high-speed tool steel (HS 18-0-1) milling knives were used for the tests (Table 2). The chemical composition of the steel HS 18-0-1 (ISO 4957 1999) is presented in Table 3. Before the tests, all the knives were sharpened in the same conditions.

The tests were done in the stand for woodcutting, specially arranged on the base of a thickness planer (SR3-6). The samples were processed according to the scheme of the longitudinal milling, when the directions of the cutting speed  $v_c$  and feed speed  $v_f$  vectors are opposite (Bendikiene and Keturakis 2017). The conditions of milling tests are presented in Table 4. Two knives were fastened in the cylindrical head of the knives, but only one took part in the cutting process. The second was used for balancing compensation.

**Table 2.** Specifications of Milling Tool

Steel	HS 18-0-1
Hardness	61 HRC
Dimensions of milling blade, mm	60 × 30 × 3
Sharpness angle $\beta$	40°

**Table 3.** Chemical Composition of HS 18-0-1 Steel

Chemical composition of the steel (wt.%)					
C	Si	Mn	Cr	V	W
0.70 – 0.78	≤ 0.45	≤ 0.40	3.80 – 4.50	1.00 – 1.20	17.5 – 18.5

**Table 4.** Milling Test Conditions

Cutting speed $v_c$ (m/s)	22, 40
Feed speed $v_f$ (m/min)	2, 4, 8
Rotational speed $v_r$ (rpm)	4080, 7420
Feed per cutter $f_z$ (mm)	0.50; 1.00
Depth of milling $h$ (mm)	2
Width of milling $b$ (mm)	45
Cutting diameter $D$ (mm)	103
Number of cutting edge $z$ (unit)	1
Cutting angle $\delta$ (degree)	60

The thickness of the chip  $a$  (mm) was changed indirectly, through the feeding per cutter  $f_z = 0.50$  mm and 1.00 mm. The samples were processed at two cutting speeds,  $v_c = 22$  m/s and 40 m/s.

The main characteristic for describing the wear of the milling tool was selected to be the rounding radius  $r$  ( $\mu\text{m}$ ) of the cutting edge. The factual values of rounding radius were determined using the method of lead imprints (Miklaszewski *et al.* 2000) and optical microscope (Nikon Eclipse E200, Tokyo, Japan), with a digital video camera (Lumenera Infinity 1, Ontario, Canada).

The values of the rounding radius  $r$  of the cutting edge were measured at the following intervals of the effective (real) tool nose cutting path  $L$ : 0 m, 50 m, 100 m, 150 m, 200 m, 400 m, 800 m, and 1600 m. The measurements were repeated five times in each interval of the path. The received results were measured and processed using a personal computer and software (Infinity Analyze Release 5.0.2, Lumenera Corporation, Ottawa,

Canada). The received results were processed using the methods of mathematical statistics, and error of radius measurement was  $\pm 2 \mu\text{m}$ .

The parameter of the processed surface roughness  $R_z$  ( $\mu\text{m}$ ) was measured by a contact stylus profilometer (Mahr MarSurf PS1, Göttingen, Germany). The radius of its diamond tip was  $2 \mu\text{m}$ , measurement angle  $90^\circ$ , and measurement length was 17.5 mm. The surface unevenness was measured in the same intervals of cutting path  $L$ : 50 m, 100 m, 150 m, 200 m, 400 m, 800 m, and 1600 m. Five sectors were selected in one sample ( $17.5 \text{ mm} \times 17.5 \text{ mm}$ ), and their roughness was measured along and across the fiber. In total 280 measurements were performed through the testing series. All measurement results were processed by Gaussian digital filter, and the roughness measurement error did not exceed  $\pm 10\%$ .

## RESULTS AND DISCUSSION

The performed tests determined the influence of the cutting path and reached rounding radius of the cutting edge on the surface roughness, when the wood samples of pine and black alder were milled along the fiber at different cutting and feed speeds (Kvietkova *et al.* 2015).

The tool was worn the most intensively in the first wear stage until the limit of cutting path  $L = 400 \text{ m}$  (Table 1). In the first stage of wear the species of wood did not have any significant influence on the wear intensity. The difference between the values of the rounding radius of the cutting edge in case of milling pine and black alder samples was from 5% to 7%. In this stage the wear of tool was expressed by mechanical crumbling and deburring of sanding scarfs on cutting edge; wood species or density were not decisive or did not affect the blunting process. When the cutting path reached the distance of 400 m, the tool wear gradually passed to the stage of monotonic wear. In this stage the intensity of rounding radius growth was reduced, and further wear of the tool was even. The microgeometry of the cutting edge changes because of temperature effect and just negligibly because of abrasive wear (Porankiewicz 2006; Pamfilov *et al.* 2014). The tool wear was observed until the cutting path of 1600 m.

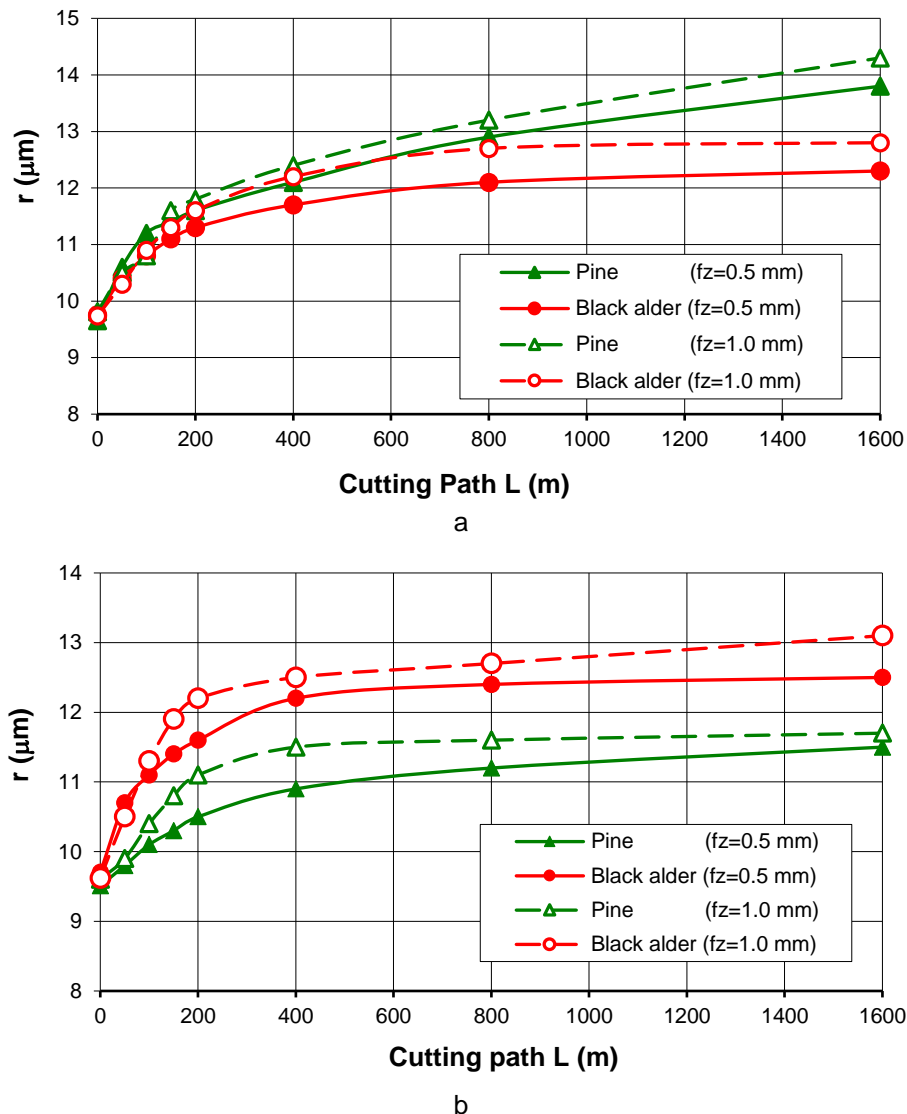
The influence of the wood species on tool wear was analyzed. The tool was worn more intensively when black alder was milled, although the density of black alder wood was lower than that of the pine wood (Table 1). However, an exception was also noticed: when the feed per cutter was  $f_z = 0.5 \text{ mm}$  and the cutting speed was increased from 22 m/s to 40 m/s, the tool wear was lower than the pine wood milling results. The best quality was achieved (Aguilera *et al.* 2016) when cutting path had exceeded 7000 m with cutting speed 44 m/s while processing pine wood (*Pinus radiata* L.). When the cutting speed increased, the large volume of the chips lost contact with the processed surface due to the pine wood tendency to split under the influence of lower cutting forces. The chip was formed easier; the true cutting length of cutter's contact with the wood was reduced compared with the milling of black alder, which tended to split less.

The influence of feed per cutter (chip thickness) on the rounding radius of the cutting edge was analyzed. When the feed per cutter increased from 0.5 mm to 1.0 mm, the intensity of the tool wear decreased. When the feed per cutter was  $f_z = 0.5 \text{ mm}$ , the most intensive wear of the tool occurred when the black alder was milled. When the pine wood was milled, the tool was worn 4% less than with black alder.

The received results are interesting for interpretation the postulates of classical

wood cutting theory. With increased feed per cutter, the chip length and the true contact of cutting edge with wood increased slightly (Csanády and Magoss 2013). Therefore, because of the chip thickness increment, the intensity of tool wear should grow. The tendency of dry wood splitting should also increase due to real friction and cutting edge wear. These effects depend on wood materials and machining factors, and they usually do not completely follow mathematical equations and models.

The results presented in Fig. 1 demonstrate a clear regularity and distinctive character of transition between initial and monotonic tool nose wear. Certainly, individual cases for different wood species differ, but wear modes suggest possibilities to create reliable modeling explaining initial and monotonic tool nose wear phenomena. Such a mechanical-tribological tool nose wear mathematical model is the objective of ongoing specialized theoretical and experimental research of the authors of this paper.

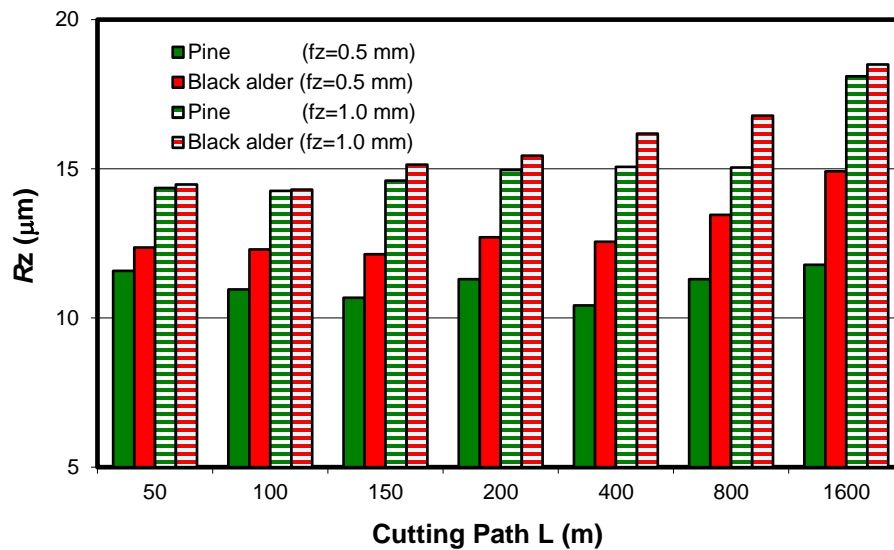


**Fig. 1.** Impact of cutting path  $L$  on the rounding radius  $r$  of the cutting edge when  $v_c$  was a) 22 m/s or b) 40 m/s

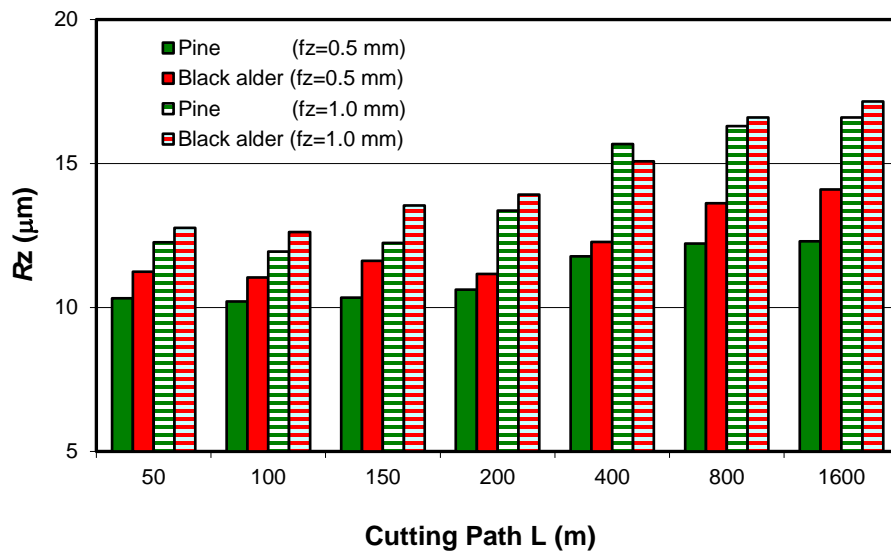
An analysis of surface roughness showed that the surface of pine wood was smoother than that of black alder (Figs. 2 and 3). This regularity did not change when the

surface roughness was measured along and across the wood fiber. The tests confirmed the theory that in case of a higher density of the wood and a lower width of rings (Table 1), a smoother surface was achieved. Although the density of pine wood was higher only by 9%, the received surface roughness  $R_z$  along the fiber was on average by 11% lower, and across the fiber,  $R_z$  was lower by 14%.

The increased cutting path and rounding radius of the tool cutting edge caused the degradation of the milled surface quality. This tendency was noticed in all cases of cutting speed and feed per cutter. The highest surface roughness was achieved while milling up to 200 m of the cutting path. From the 200 m to 800 m limit, the surface roughness along and across the fiber increased gradually. As expected, the highest numeric values of the surface roughness  $R_z$  were achieved with cutting path of 1600 m.



a

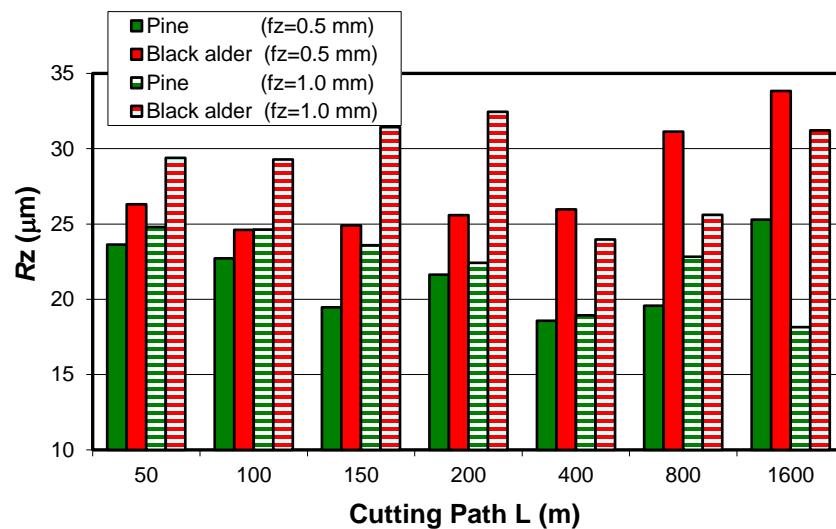


b

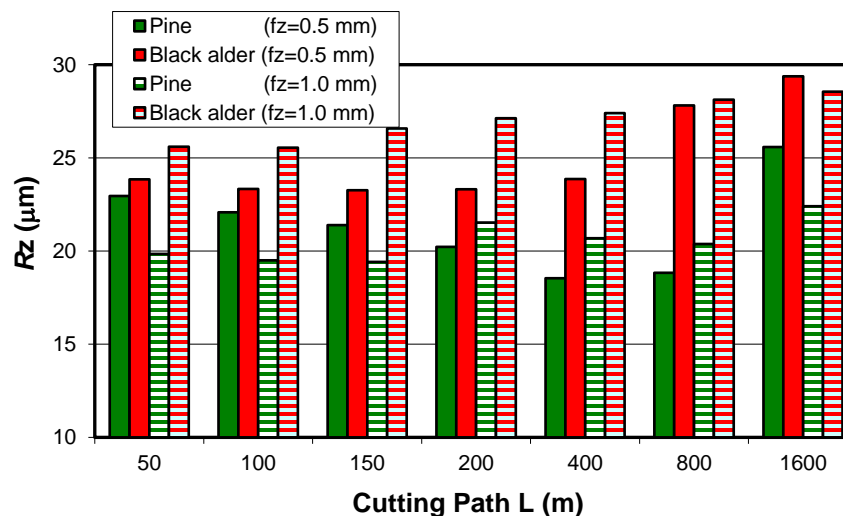
**Fig. 2.** Cutting and feed speed effects on surface roughness  $R_z$  along the fiber when  $v_c$  was a) 22 m/s or b) 40 m/s

When the feed per cutter was increased, the surface roughness also increased. The best quality of the surface was reached when the feed per cutter was  $f_z = 0.5$  mm, when  $f_z = 1.0$  mm led to lower quality; it did not depend on the species of wood and cutting speed. The lowest increase of numeric values of surface roughness  $R_z$  was noticed while processing pine wood.

When the cutting speed was increased from 22 m/s to 40 m/s, the roughness of pine wood was decreased on average by 12% and that of black alder by 7%. This surface tendency remained in various segments of cutting path when the cutting speed was increased. Thus, the increased cutting path intensified the wear of the tool but with different dynamics of blunting. When the wood was milled with a blunt tool, an irregular milling process occurred, during which the top layers of the fibers on the newly formed surface were deformed and compressed with different intensity and in different depth.



a



b

**Fig. 3.** Cutting and feed speed effects on surface roughness  $R_z$  across the fiber when  $v_c$  was a) 22 m/s or b) 40 m/s



In contrast to the above-presented hypothesis to explain and model tool nose wear phenomena, the variations in surface roughness (Fig. 3) showed more practical tendencies than theoretical regularities. However, some stochastic roughness behavior at the initial cutting path up to 400 m and following monotonous surface formation was noticed. This result confirmed presumptions on extreme importance of enhancing knowledge on tool wear and surface formation stages and dynamics to facilitate evolution of tools, creation eco- and energy-effective cutting processes and highly productive wood machining.

## CONCLUSIONS

1. The milling tool exhibited the most intense wear in the first 400 m of cutting path. After 400 m, the milling tool wear gradually became monotonic.
2. The tool showed more intense wear when black alder was milled; the tool wear was 6% lower when pine wood was milled.
3. With increased feed and cutting speeds, the intensity of the tool wear was reduced.
4. The rounding radius of the milling tool cutting edge had the most influence on the roughness of the milled surface along and across the fiber. The best quality of the surface was reached when a sharp ( $r \leq 13 \mu\text{m}$ ) milling tool was used in the segment up to 400 m of the cutting path. When the rounding radius of the tool cutting edge increased, the quality of the processed surface decreased.
5. When the feed per cutter increased, the quality of the processed surface decreased. The best quality of the surface was reached when the feed per cutter  $f_z$  was 0.5 mm, which did not depend on the species of wood and cutting speed.
6. When the cutting speed increased, the quality of the processed surface increased. The best quality of the surface was reached when the cutting speed  $v_c$  was 40 m/s.
7. The surface quality of pine wood milled under the same conditions was higher than that of black alder. The surface roughness  $R_z$  of pine wood was lower on average by 11% along the fiber and by 14% across the fiber.

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