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# SURFACE QUALITY OF MILLED BIRCH WOOD AFTER THERMAL TREATMENT – WAVINESS PROFILE ($W_a$)

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## Abstract

*This paper focuses on the surface quality assessment of thermally modified birch wood after plane milling while taking into account technological parameters which have substantial effects on the processed wood surface's arithmetic mean deviation of the waviness profile ($W_a$). The milling process was affected by the cutting speed, varying from 20 to 60 m/s and with the feed speed of 4, 8, and 11 m/min. The results obtained on the set of thermally modified test samples, were compared with the results obtained on test samples without heat treatment. The surface finish was measured using various milling parameters. The results indicate that the thermal modification of wood influenced significantly neither the waviness profile, nor the roughness profile. Cutting speed and feed speed had the most significant effects among the monitored factors on both the waviness and roughness profile. The lowest waviness value was determined at the minimum feed speed, to wit 4 m/min, and its value increased altogether with the feed speed. The lowest waviness was tracked at the second highest cutting speed of 40 m/s. As for the roughness, its lowest value was achieved also when the minimum feed speed was used. It was due to direct proportionality between the value of feed speed and roughness. On the other hand, the relation is opposite in a case of cutting speed.*

**Key words:** *ThermoWood, plane milling, feed speed, cutting speed, surface waviness, surface roughness*

## INTRODUCTION

Wood has a very wide range of uses, primarily in construction, the furniture industry, the paper industry etc. One of wood's most important properties is its natural durability, especially regarding its resistance to biological pests. For all machining processes, it is necessary to select an appropriate tooling material, one with its cutting edge suitably treated to protect it from wear. (Békés *et al.* 1999)

Milling is machining with a rotary tool (cutter, milling head, *etc.*), where the nominal shaving thickness (e.g. stock removal depth) increases from zero to a maximum figure knowing that, its value is lower than the thickness of the workpiece and tool radius, with cycloid cutting motion and chip thickness within the limits $0 < h < h_{max}$ (Fig. 1). Besides, the material is fed at a right or approximately right angle to the cutter's axis of rotation (Lisičan 1996). It is the most widespread method for producing flat, contoured and rotating

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surfaces, grooves, finger joints, and the like. The main movement is rotation, which is made by the cutter, while the work piece makes the remaining movements.

It is possible to mill along the edge of the cutter, aka peripheral milling. Two categories of peripheral milling exist: conventional milling, where the cutter rotates against the direction of feed, and climb (aka parallel) milling, in which it turns in the direction of the feed (Řasa and Gabriel 2000). Selecting the type and subsequent maintenance of the tool (cutter) is very important and also requires attention. An advantage of milling is its relatively high output capacity and high-quality surface finish.

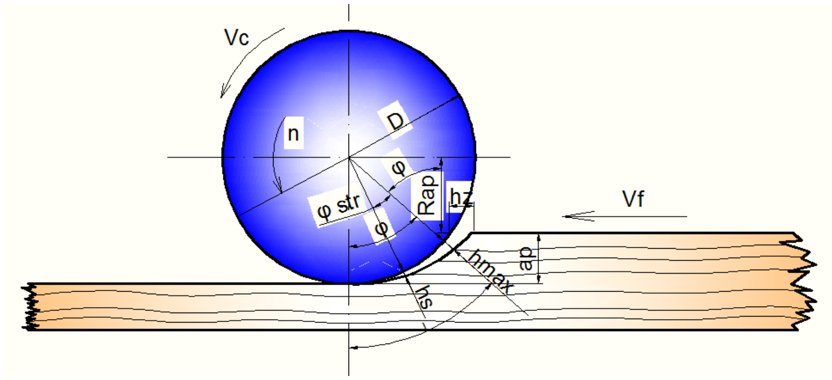

**Fig. 1.** Theoretical calculation of thickness and length of milled chip from peripheral milling; $V_f$ is feed rate (m/min), $V_c$ is cutting speed (m/s), $h_{max}$ is maximum thickness (mm), $h_s$ is cut shaving thickness (mm), $a_p$ is cut depth (m), $f_z$ is feed per tooth (mm), $n$ is tool rotation frequency (cutter rotating speed) (min$^{-1}$), $D$ is tool (cutter) diameter (m), $R$:$a_p$ is cut depth–tool radius ratio, $\varphi$ is tooth cutting angle (°), and $\varphi_{str}$ is central angle (°)

ThermoWood® is thermally modified wood that obtains its innovative internal structure through treatment using only heat and steam. This method was invented and registered in Finland. Thermal treatment positively affects and improves not only the durability, but also other physical and mechanical properties (Maulis 2009) of the wood, the interaction between wood and coatings among others. Therefore, the quality of the surface machining of thermally-treated wood is important.

During thermal treatment, the wood is treated at high temperatures ranging from 150 to 260 °C (Kačíková and Kačík 2011). Greater durability and resistance to fungi and other biological pests characterize thermally modified wood. But its mechanical properties are decreased. (Boonstra *et al.* 2007; Gündüz *et al.* 2008; Niemz *et al.* 2010; Kačík *et al.* 2012; Pelit *et al.* 2014) ThermoWood exhibits very good properties, irrespective of use (interior or exterior), which are similar to those of hard resistant wood species which do not grow in Europe.

Machining is a technological process in which the workpiece is cut into the required shape at certain defined dimensions with the required surface finishes. For thermally modified wood, it is important that the machine tools are well sharpened and the finished surfaces are as smooth as possible. The purpose of machining is an achievement of the smoothest surface possible. The main factor affecting surface finish is the tool, in terms of both the material from which it's made and its service life. Among the criteria used, the machining process concerns shape precision, the workpiece's surface finish, and dimensional precision (Ondra 1998). Each technological operation that disturbs the workpiece's original properties and integrity leaves characteristic irregularities on the machined surface.

According to ČSN EN ISO 4287 (1999), these irregularities can cause microscopic changes in the machined surface's roughness, as well as creating macroscopic transformations such as waviness, scores, troughs, and torn out fibers. Surface finish, which consists of roughness, waviness, and lay, decisively affects the properties and behavior of the component in operation (*e.g.*, the course of wear, fatigue properties, bonding strength, and kinematic and dynamic surface connections).

Vibrations, deformations in the workpiece, and material hardening can cause waviness. It is considered to be an effect from the machine, such as from imbalanced grinding wheels, imprecision in guide parts, or low stiffness or imprecision in guide screws. The waviness profile is a profile acquired by gradually applying the $\lambda_f$ and $\lambda_c$ filters to the primary profile. It is acquired by suppressing long-wave components from the primary profile using $\lambda_f$, and short wave components using $\lambda_c$ by means of a band-pass filter (Studený and Kusmič 2007).

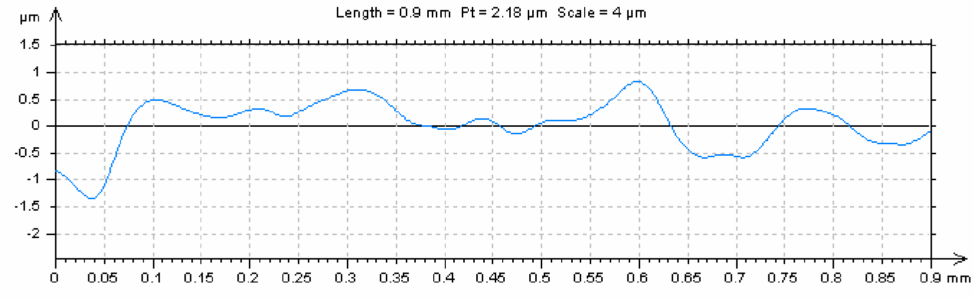

**Fig. 2.** Course of waviness in a profile

Waviness - the imperfection of the wood surface recognizable on macroscopic level - appears on the surface with regularly repeating peaks and troughs of almost identical shapes and dimensions. The surface finish parameter of waviness is understood as very small deviations from the required (ideal) shape or dimension, which substantially affects further processing of the piece, specifically its surface finish.

Issues related to this surface property of wood subjected to different types of mechanical processing have been addressed by multiple authors. However, works concerning the surface machining of wood by milling are less prevalent. Due to important impacts of surface waviness on further processing of the wood, altogether with impacts of roughness, we investigate these in two separate parts of our paper. The 1st part focuses on the waviness and the 2nd part on roughness.

## EXPERIMENTAL

### Materials

Silver birch (*Betula pendula* Roth.) from Poľana, which is east of Zvolen, Slovakia, was used. The parts of the wood chosen for sample preparation were in the middle of the wood, between the pith and bark. These parts were cut into 100-cm-long pieces. Defectless samples with dimensions 40 × 100 × 500 mm were used for the experiments. All samples were conditioned for 4 months in a conditioning room ($\phi$ = (65 ± 3) % and $t$ = (20 ± 2) °C) to achieving 12% equilibrium moisture content (EMC). Birch wood had a density of 550 kg/m$^3$ in oven-dry state. After conditioning, the samples were divided into two groups. The first group contained samples intended for thermal treatment and the second group consisted of reference samples of native wood. The whole investigation involved 450 samples.

### Procedure

*Thermal treatment*

Wood samples were placed on a metal grate and subsequently placed into the thermal chamber model S400/03 (LAC Ltd., Czech Republic) (technical parameters are indicated in Table 1). The heat treatment was carried out in three phases according to ThermoWood® process developed by VTT, Finland. The first phase consisted of drying the wood and heating the chamber to the desired temperature, from 160 to 240 °C using steam as a protective vapor. In the second stage, the desired temperature was maintained for the specified time (5 h) (Table 2). In the third and last phase, the chamber and wood were gradually cooled. During this phase, the wood is re-moisturized in order to achieve the end-use moisture (5 – 7 %). The thermally modified samples were then conditioned ($\phi$ = (65 ± 3) % and $t$ = (20 ± 2) °C) for three weeks. Before experiments, all samples were machined to final thickness (25 mm) using a thickness planer DHM 630P (Holzmann, Germany). Native and thermally-modified samples (final dimensions 25 × 100 × 500 mm) were prepared for the plane milling process.

**Table 1.** Parameters of Thermal Chamber

| **Input technical parameters** | |
|---|---|
| Moisture content of wood | 12 % |
| Filling capacity of TW furnace | 0.38 $m^3$ |
| Power consumption | 6 kWh |
| Maximum temperature reached | 160 °C, 180 °C, 210 °C, and 240 °C |

**Table 2.** The Duration of Thermal Treatment

| **Final thermal temperature** (°C) | **Thermal treatment** | | | |
|---|---|---|---|---|
| | **I. phase** (hours) | **II. phase** (hours) | **III. phase** (hours) | **Total time** (hours) |
| 160 | 4 | 5 | 2 | 11 |
| 180 | 5 | 5 | 2.5 | 12.5 |
| 210 | 6 | 5 | 3 | 14 |
| 240 | 7 | 5 | 3.5 | 15.5 |

*Plane milling*

The milling process was carried out using an FVS mill with a STEFF 2034 automatic feeder (Maggi, Italy). A stock removal height was of 1 mm per pass. Cutter parameters and individual cutting angles were as follows:

| FVS with feed system STEFF 2034 | Cutter Head |
|---|---|
| - Input power 4 kW, | - Rake angle γ 25, 20, 15°, |
| - RPM 3000, 4500, 6000, | - Cutting angle of wedge β 45°, |
| - Cutting speed 20, 40, 60 m/s, | - Clearance angle α 20, 25, 30, |
| - Feed speed 4, 8, 11 m/min. | - Cutting angle δ 65, 70, 75. |

**Methods**

The waviness profile was measured according to ISO 4287 (1997) and ISO 4288 (1996) using a Form Talysurf Intra roughness meter (Taylor-Hobson, UK). The measurement was carried out in three tracing lengths oriented in a parallel direction with respect to the length of the sample and the feed direction. The track length was 50 mm. The waviness profile was evaluated based on the arithmetic mean deviation of the waviness profile $W_a$.

**Evaluation and Calculation**

The influence of factors on waviness was statistically evaluated using ANOVA, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

The density was determined before and after treatment. Density was calculated according to Eq. 1 from ISO 13061-2 (2014),

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

where $\rho_w$ 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 the 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 moisture content of samples was determined according to ISO 13061-1 (2014) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

where $w$ is the moisture content of the sample (%), $m_w$ is the mass (weight) of the test sample at certain moisture $w$ (kg), and $m_0$ is the mass (weight) of the oven-dry test sample (kg). Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014).

## RESULTS AND DISCUSSION

Based on the significance levels given in Table 3, the feed rate can be considered to have had a significant effect, whereas the cutting speed and thermal treatment did not exhibit significant effects on arithmetic mean deviation of the waviness profile ($W_a$). Furthermore, the interaction among the three monitored factors resulted in a significant effect neither.

These results are shown respectively in Fig. 3, 4, 5 and 6 Costes and Larricq (2002) also found that the increase of cutting speed does not have any effect on the value of waviness profile ($W_a$) and Keturakis and Juodeikienė (2007) also found that was an effect of increase in feed speed on the monitored characteristic. Clearly higher arithmetic mean deviations of the waviness profile for thermally modified wood in the range of 160 to 210 °C, however outside the limit for statistical significance is also claimed by the works of Budakçı *et al.* (2011, 2013)

**Table 3.** Individual Factors' Effects on Arithmetic Mean deviation of the Waviness Profile

| Monitored factor | Sum of squares | Degrees of freedom | Variance | Fisher's F - Test | Significance level P |
|---|---|---|---|---|---|
| **Intercept** | 8,383.342 | 1 | 8,383.342 | 1,970.573 | 0.000 |
| **Cutting speed** | 17.445 | 2 | 8.722 | 2.050 | 0.131 |
| **Feed rate** | 120.021 | 2 | 60.011 | 14.106 | 0.000 |
| **Treatment** | 34.476 | 4 | 8.619 | 2.026 | 0.091 |
| **Cutting speed + Feed rate + Treatment** | 49.171 | 16 | 3.073 | 0.722 | 0.771 |
| **Error** | 1,340.094 | 315 | 4.254 | | |

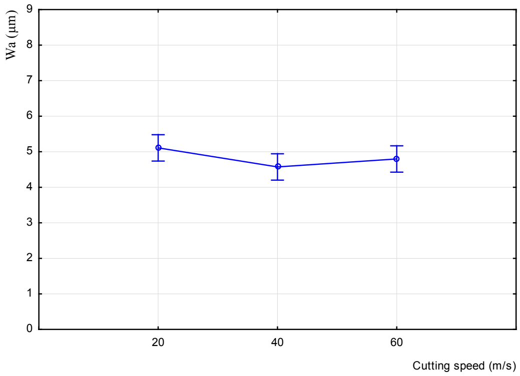

**Fig. 3.** Cutting speed's effect on arithmetic mean deviation of the waviness profile

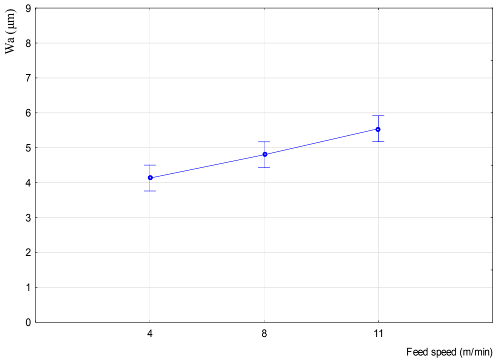

**Fig. 4.** Feed rate's effect on arithmetic mean deviation of the waviness profile

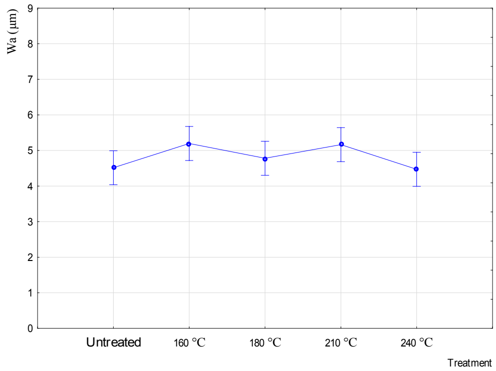

**Fig. 5.** Thermal treatment's effect on arithmetic mean deviation of the waviness profile

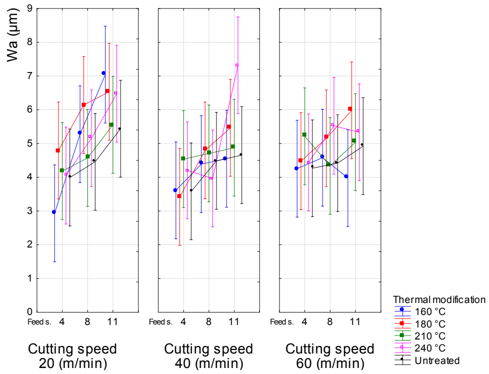

**Fig. 6.** Combined effect of cutting speed, feed rate, and thermal treatment on arithmetic mean deviation of the waviness profile

Based on these graphical outputs, the effect of cutting speed on the monitored variables is apparent. The arithmetic mean deviation of the profile waviness decreased with increased cutting speed. In contrast, increases in the monitored parameter were observed after increases in the feed rate. For high-quality machining, it is necessary for the cutting speed to be sufficiently high relative to feed rate, as higher feed rates resulted in diminished quality of the machined surface finish.

## CONCLUSIONS

1. Based on the results, it can be stated that thermal treatment did not have a significant effect on surface finish, expressed as the arithmetic mean deviation of the waviness profile of birch wood in plane milling.
2. Increases in cutting speed during plane milling decreased the arithmetic mean deviation of the waviness profile.
3. Changes in feed rate had the opposite effect, as increasing this parameter increased the arithmetic mean deviation of the waviness profile.
4. Cutting speed affected the finish of the machined surface. To achieve a higher-quality surface finish, it is necessary to select a high cutting speed, as well as the lowest possible feed rate.

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