Effect of Selected Parameters on the Surface Waviness in Plane Milling of Thermally Modified Birch Wood

Milan Gaff,[a, *] Monika Kvietková,[a] Miroslav Gašparík,[a] Lukáš Kaplan,[a] and Štefan Barcík [b]

This article focuses on the plane milling of thermally modified birch wood while taking into account technological parameters that have substantial effects on the processed wood surface's average waviness profile deviation (W_a). The milling process was affected by the cutting speed, which varied from 20 to 60 m/s, with a feed rate of 4, 8, and 11 m/min. The results obtained on the set of thermally modified test specimens, were compared with the results obtained on test specimens without heat treatment. The surface finish was measured using various milling parameters. The material removal was 1 mm per pass. The results indicate that the thermal processing of wood did not significantly influence the arithmetic average deviation of the roughness profile (R_a). Cutting speed and feed rate had the most significant effects among the monitored factors. The lowest arithmetic average deviation of the roughness profile (R_a) was determined at a feed rate of 4 m/min and cutting speed of 40 m/s. An increase in cutting speed led to a decrease in the average roughness, while increased feed rate had the opposite effect.

INTRODUCTION

Wood has a very wide range of uses, primarily in construction, the furniture industry, the paper industry, and transport. 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 increases from zero to a maximum figure, and the material is fed at an angle to the cutter's axis of rotation (Lisičan 1996). It is the most widespread method for producing flat and contoured surfaces, grooves, finger joints, and the like. The main movement is rotation, which is made by the cutter, while the work piece (or with some machines the headstock) makes the remaining movements.

The purpose of milling is to process or machine a component through cutting (a process that forms shavings) into the required dimensions, shape, and surface finish. Milling is a very widely used wood processing technology. It is possible to mill along the edge of the cutter, which is known as peripheral milling. Depending on the rotation direction, peripheral milling can be divided into two categories: conventional milling,

bioresources.com

where the cutter rotates against the direction of feed, and climb 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. It is used to machine flat, contoured, and rotating surfaces. Milling is also used to machine grooves of various profiles, as well as to create finger joints.
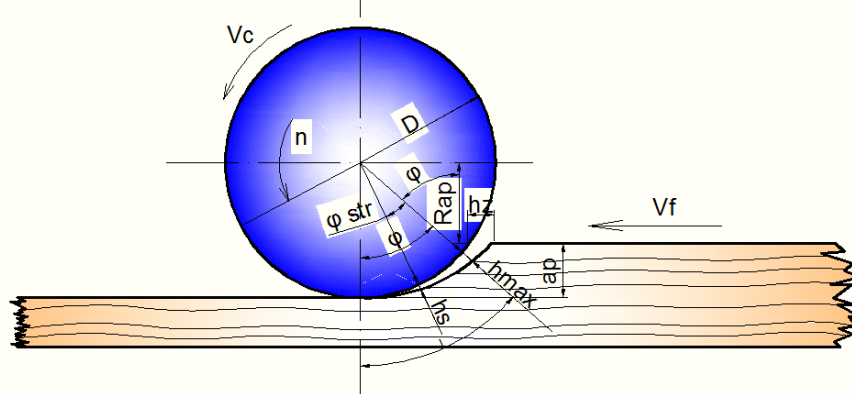

Fig. 1. Theoretical calculation of thickness and length of milled chip from peripheral milling; V_f is feed rate (m/min), V_c is cutting speed (m/s), h_{max} is maximum thickness (mm), h_s is cut shaving thickness (mm), a_p is cut depth (m), f_z is feed per tooth (mm), n is tool rotation frequency (cutter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

ThermoWood is thermally modified wood that obtains its innovative internal structure through thermal and moisture treatment. This method was invented and registered many years ago in Finland. ThermoWood is modified using only heat and steam, and the entire production process is completely environmentally friendly. Thermal treatment positively affects and improves not only the durability, but also other physical and mechanical properties (Maulis 2009).

During thermal treatment, the wood is thermally and hydrothermally 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. Wood modified in this manner exhibits very good properties, which are similar to those of rare tropical wood, a fact that attracts great attention for this modern material, primarily among more demanding customers and those who prefer luxury products. This material has increased in popularity because its beneficial properties cannot be found in natural wood growing in Europe. Additionally, ThermoWood has both interior and exterior uses.

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. Thermal treatment even facilitates the tool's penetration capabilities into the workpiece.

All machining, including of course milling, is designed with the intention of achieving the smoothest surface possible. A surface is defined as the interface between two distinct environments – the basic material and its surroundings. This interface defines the overall appearance of the given material. The product's surface finish can generally be defined as a set of properties specified by the producer, consumer, and price-setting bodies according to various criteria (Prokeš 1982). The overall finish of the machined surface is influenced by many factors. The main factor affecting surface finish is the tool, in terms of

bioresources.com

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 λ_f and λ_c filters to the primary profile. It is acquired by suppressing long-wave components from the primary profile using λ_f, and short wave components using λ_c by means of a band-pass filter (Studený and Kusmič 2007).
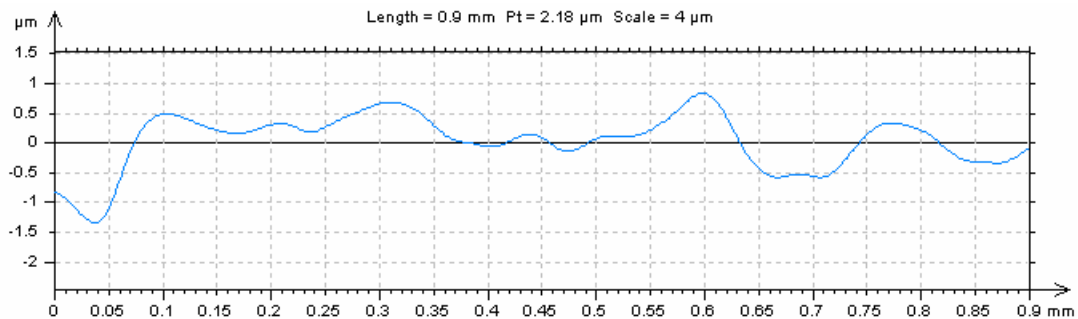

Fig. 2. Course of waviness in a profile

Waviness 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 nevertheless substantially affects further processing of the piece, specifically its surface finish.

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 $40 \times 100 \times 500$ mm were used for the experiments. All samples were conditioned for 4 months in a conditioning room ($\phi = (65 \pm 3)$ % and $t = (20 \pm 2)$ °C) to achieve 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 ($\phi = (65 \pm 3)$ % and $t = (20 \pm 2)$ °C) for three weeks. Before experiments, all samples were machined to final thickness (25 mm) using a DHM 630P thickness planer (Holzmann, Germany). Native and thermally-modified samples (final dimensions $25 \times 100 \times 500$ 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. 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). Cutter parameters and individual cutting angles were as follows.

FVS with feed system STEFF 2034
-   Input power 4 kW,
-   RPM 3000, 4500, 6000,
-   Cutting speed 20, 30, 40 m.s^{-1},
-   Feed speed 4, 8, 11 m.min^{-1}.

Cutter Head
- Rake angle γ 15, 20, 25°,
- Cutting angle of wedge β 45°,
- Clearance angle α 20, 25, 30,
- Cutting angle δ 70, 75, 80.

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 roughness 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),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \qquad (1)$$

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 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,

$$w = \frac{m_w - m_0}{m_0} * 100 \qquad (2)$$

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. Furthermore, the interaction among the three monitored factors did not result in a significant effect.

The data presented in Table 3 clearly indicate that cutting speed did not have a significant effect on the arithmetic average deviation of the waviness profile (Wa). These results confirm the results shown in Fig. 3.

Costes and Larricq (2002) also found that the increase of cutting speed does not have any effect on the value waviness profile (W_a).

The values shown in Fig. 4 clearly illustrate the significant effect that feed rate had on the monitored characteristic, as the arithmetic average deviation of the waviness profile (Wa) increased as the feed rate increased. Keturakis and Juodeikienė (2007) also found the same effect of the feed speed on the monitored characteristic.

Table 3. Individual Factors' Effects on Arithmetic Average Deviation of Waviness Profile

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Overall diameter	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		
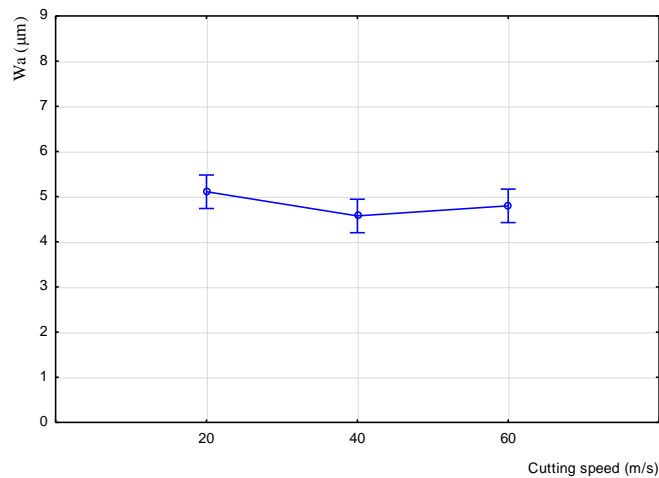
Fig. 3. Cutting speed's effect on arithmetic average deviation of waviness profile
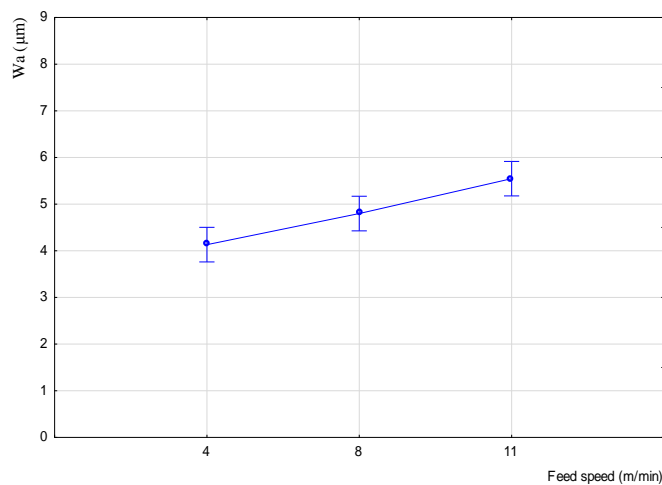
Fig. 4. Feed rate's effect on arithmetic average deviation of waviness profile

bioresources.com

The values in Fig. 5 clearly indicate higher arithmetic average deviations for the waviness profile for thermally modified wood in the range of 160 to 210 °C, although these differences were small and slightly outside the limit for statistical significance. These conclusions were also found in the works of Budakçı *et al.* (2011, 2013). (2013). Figure 6 illustrates that the machined material's resulting waviness was not affected after the birch wood was thermally treated.
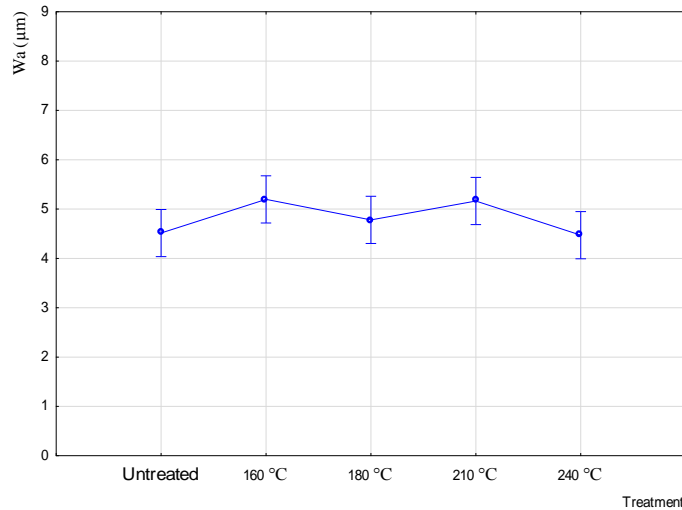

Fig. 5. Thermal treatment's effect on arithmetic average deviation of waviness profile
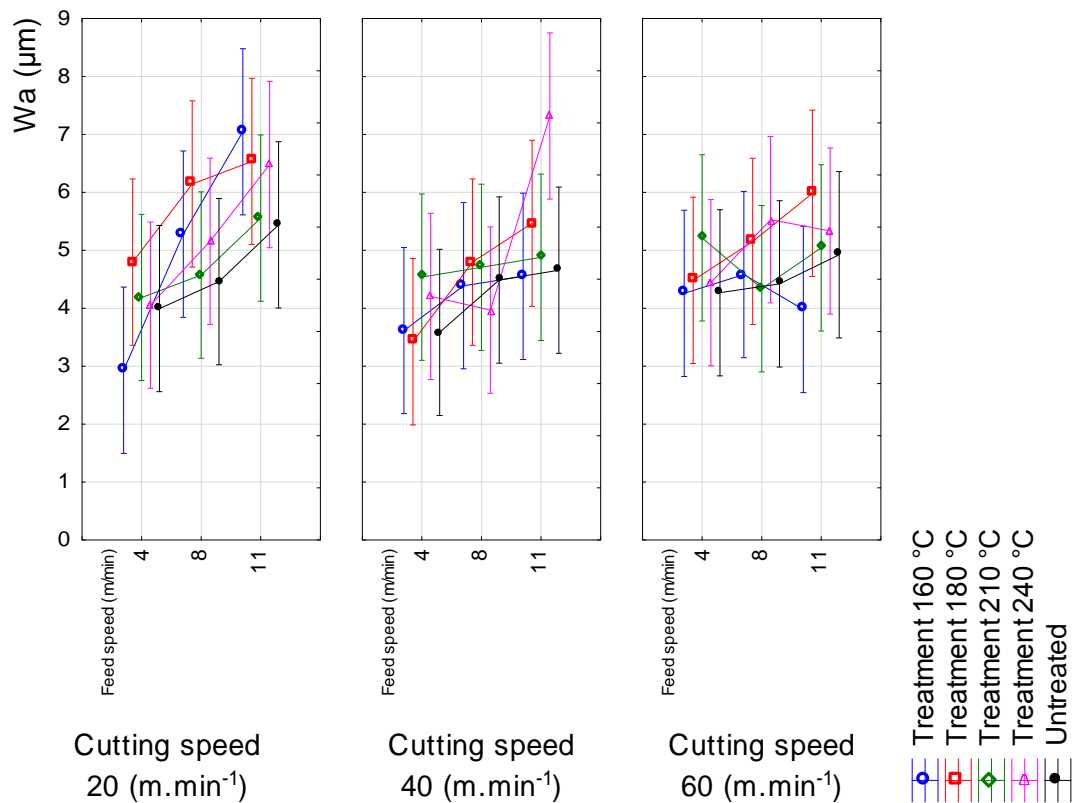

Fig. 6. Combined effect of cutting speed, feed rate, and thermal treatment on arithmetic average deviation of waviness profile

Based on these graphical outputs, the effect of cutting speed on the monitored variables is apparent. The arithmetic average deviation of the waviness profile 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 average deviation of the waviness profile of birch wood in plane milling.

2. Increases in cutting speed during plane milling decreased the arithmetic average deviation of the waviness profile.

3. Changes in feed rate had the opposite effect, as increasing this parameter increased the arithmetic average 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.

ACKNOWLEDGMENTS

REFERENCES CITED

Békés, J., Hrubec, J., Kicko, J., and Lipa, Z. (1999). *Teória Obrábania* [*Theory of Machining*], Vydavateľstvo STU, Bratislava. (in Slovak)

Budakçı, M., İlçe, A. C., Gürleyen, T., and Utar, M. (2013). "Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine," *BioResources* 8(4), 3189-3199. DOI: 10.15376/biores.8.3.3189-3199

Budakçı, M., İlçe, A. C., Korkut, D. S., and Gürleyen, T. (2011). "Evaluating the surface roughness of heat-treated wood cut with different circular saws," *BioResources* 6(4), 4247-4258. DOI: 10.15376/biores.6.4.4247-4258

Costes, J.-P., and Larricq (2002). "Towards high cutting speed in wood milling," *Annals of Forest Science* 59(8), 857-865. DOI: 10.1051/forest:2002084

ČSN EN ISO 4287. (1999). "Geometrické požadavky na výrobky (GPS) - Struktura povrchu: Profilová metoda - Termíny, definice a parametry struktury povrchu. [Geometrical product specification (GPS) - Surface texture: Profile method, Terms, definitions and surface texture parameters]," Czech Office for Standards, Metrology and Testing, Prague. (in Czech)

bioresources.*com*

ISO 13061-1 (2014). "Physical and mechanical properties of wood -- Test methods for small clear wood specimens -- Part 1: Determination of moisture content for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

ISO 13061-2 (2014). "Physical and mechanical properties of wood -- Test methods for small clear wood specimens -- Part 2: Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

ISO 4287 (1997). "Geometrical product specifications (GPS) -- Surface texture: Profile method -- Terms, definitions and surface texture parameters," *International Organization for Standardization*, Geneva, Switzerland.

ISO 4288 (1996). "Geometrical product specifications (GPS) -- Surface texture: Profile method -- Rules and procedures for the assessment of surface texture," International Organization for Standardization, Geneva, Switzerland.

Kačíková, D., and Kačík, F. (2011). "Chemické a Mechanické Zmeny Dreva pri Termickej Úprave [Chemical and Mechanical Changes during Thermal Treatment of Wood]," Technical University in Zvolen. (in Slovak)

Keturakis, G., and Juodeikienė, I. (2007). "Investigation of milled wood surface roughness," *Materials Science (Medžiagotyra)* 13(1), 47-51.

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

Maulis, V. (2009). "Technologie a Zhodnocení Vybraných Vlastností Dřeva Modifikovaného Teplem [Production Technology and Evaluation of Thermal Modified Wood]," M.S. thesis, Czech University of Life Sciences, Prague, Czech Republic (in Czech).

Mitutoyo. (2013). *Metrologická Příručka pro Přesné měřící Přístroje. [Metrological Handbook for Precise Measuring Equipment]*, Mitutoyo Česko s.r.o., Teplice. (in Czech).

Ondra, J. (1998). "Optické metódy pre monitorovanie kvality obrobených povrchu. [Optical methods for monitoring machined surface quality]," *Kvalita a Spoľahlivosť Strojov: 3. Medzinárodné Vedecké Sympózium* 20–21, 201-205. (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).

Řasa, J., and Gabriel, V. (2000). *Strojírenská Technologie 3. Metody, Stroje A Nástroje Pro Obrábění, 1. Díl. [Engineering Technology 3. Methods, Machinery and Instruments for Machining, Part 1]*, Prague, Scientia. (in Czech)

Studený, Z., and Kusmič, D. (2007). "Hodnocení povrchu biokompatibilního hydroxyapatitového povlaku na titanové slitině [Surface evaluation of biocompatible hydroxyapatite film on titanium alloy]," *Technológia 2007: Zborník prednášok.1 10. medzinárodná konferencia*, 19–20 Bratislava, 32. (in Slovak)