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# EVALUATION OF THE EFFECT OF INDIVIDUAL PARAMATERS OF OAK WOOD MACHINING AND THEIR IMPACT ON THE VALUES OF WAVINESS MEASURED BY A LASER PROFILOMETER

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## ABSTRACT

This article deals with determining the effect of different degrees of thermal modification, different cutting speeds (20, 30, 40 $m \cdot s^{-1}$), different feed rates (4, 8, 11 $m \cdot min^{-1}$) and different rake angles (15, 20 and 25°) with a 1 mm layer of removed material, on the quality of the surface of the workpiece using the mean arithmetic variation of the waviness profile „Wa". The release was secured by setting the ruler and firmly holding it in the desired position. The ruler so configured was all the time to milling all the setting options.The article evaluates the process of planar milling of natural and thermally modified oak wood (*Quercus cerris*). For the evaluation, the samples were thermally modified by the Thermowood process at a temperature range of 160-210°C. The quality of the treated surface was evaluated after the planar milling process. The results obtained from this research show that by increasing the cutting speed during the machining of thermally modified and natural oak wood, we achieve better values of the mean arithmetic deviation of the waviness profile. The values of the monitored characteristic can also be improved by lowering the feed rate and selecting an appropriate rake angle. Thermal modification always lowers the values of the monitored characteristic.

KEYWORDS: Surface roughness, surface waviness, Thermowood, planar milling, machining parameters.

## INTRODUCTION

Wood as a raw material that is widely used by man has been used in exteriors and interiors for thousands of years. Today, wood used in the exterior must meet specific quality requirements;

the external factors that it is exposed to may cause a deterioration in its mechanical and aesthetic properties. Wood that is exposed in this way must exhibit high dimensional stability, high resistance and good aesthetic properties throughout its use (Kokutse et al. 2006).

Most commonly, chemical methods are used to protect wood. By coating, soaking and vacuum-impregnating the wood, we can achieve very good wood protection against biotic and abiotic factors. To protect the wood against UV radiation, we can use coatings with UV filters. This chemical protection of wood is very ecologically demanding, not only during the application of the protection, but also during its use and often even when it is disposed of. Another wood protection method is thermal modification. During thermal modification, wood is exposed to a high temperature under atmospheric pressure and a normal or reduced oxygen content (Brito et al. 2006). During the thermal modification process, wood is exposed to temperatures in the range of 100-250°C (Guedira 1988, Vovelle and Mellottee 1982). The higher the modification temperature, the darker the color of the modified wood (Kačíková et al. 2011, Gündüz et al. 2008). In comparison to wood that is not thermally modified, thermally modified wood has higher dimensional stability, lower hygroscopicity, color changes, and a higher resistance to wood-decay fungus and weather conditions (Johansson 2008).

Thanks to the new properties that wood obtains through thermal modification, it is particularly suitable for exterior and interior use. Thanks to all the mentioned properties, thermal modification can be considered a sustainable solution that adds value to natural wood. Thermally modified wood is currently machined using the same technological equipment as natural wood without thermal treatment, one of the most important technological processes being milling.

Due to its wide application, milling is currently considered to be the most commonly used wood machining process. The basic technological milling methods are curved surface milling, profile milling and planar milling. Planar milling is the most common of the technological processes. The achievable surface quality depends on the tool, the material properties and the actual process of creating the newly machined surface. In the planar milling process, the sliding movement of the workpiece and rotary movement of the tool occur linearly, resulting in a cycloidal movement of the tool blades (Kvietková et al. 2015a, c, Gaff et al. 2016, Kubš et al. 2016). This affects the quality of the machined surface, because the cycloidal motion of the tool results in the formation of waviness on the newly created surface. According to Lisičan (1996), the blade path forms a cycloid on the workpiece; since the cutting speed is much higher than the feed rate, we can consider the path to be a circle.

We also distinguish parallel and counter milling. The most common wood milling processes use counter milling. We most often see this in planers and thicknessers, as well as four-sided machining centers, where planing and thicknessing is performed.

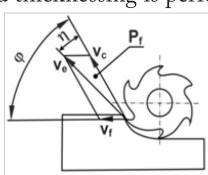


*Fig. 1: Counter milling.*
*vc – cutting speed, vf – feed rate, φ – contact angle between the wood fiber and the tool.*

In counter milling, the cutting force is directed into the material, which allows for lower clamping forces. This results in less tool vibration, and the feed rate can be increased. During parallel milling, the blades are subjected to impact stress, which causes them to dull quickly.

During the machining process, particularly forces passing through the tool act on the workpiece. These forces result in chip separation and the machining itself. The whole process is influenced by other parameters.

The basic parameters include technological parameters, such as cutting speed, feed rate and removal size. The second most important parameter is the angular geometry of the tool, including the cutting edge angle, rake angle and clearance angle of the tool. The above mentioned parameters have the greatest effect on the quality of the surface we obtain by the machining. The resulting quality is very important for further surface treatment.

The quality of the machined surface can be determined by a number of methods, from basic methods such as the use of a comparison microscope, to the use of a contact-type roughness meter and high-precision devices such as a laser profile gauge. We can evaluate many characteristics on the monitored surface. We always choose only one or a few characteristics that are important with regard to the further processing of the newly acquired surface. In terms of the quality of surface machined with planar milling, we particularly assess the average arithmetic deviation of the waviness profile or the waviness of the surface "Wa".

We encounter waviness in planar milling, where the rotary motion of the tool is opposed by the linear movement of the workpiece, which is when the blades travel along a cycloid. This mutual interaction of motions causes the uneven waviness on the machined surface. Waviness is defined as regularly repeating ridges and depressions of generally the same order and size (Kvietková et al. 2015b, d, Kminiak and Gaff 2015,Kaplan 2015).

## MATERIAL AND METHODS

### Materials

The oak wood was logged in the Vysočina region near Polná in the Czech Republic. For the production of the samples, radial sections of wood were selected - the machining and measuring were therefore performed on tangential sections. The size of the prepared samples was 20 x 100 x 450 mm (th x w x l)(longitudinal cross cutting model). The samples were divided into four groups – wood thermally modified at 20°C (without thermal modification), and wood thermally modified at 160°C, 180°C and 210°C (Fig. 2).

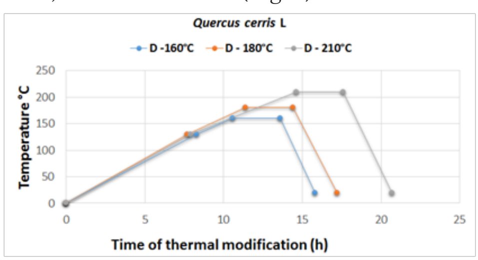


*Fig. 2. The thermal modification process specimens (T – 160 °C , T – 180 °C, 210 °C).*

Next, the thermal modification was performed, which was carried out using the standard Thermowood process. The wood was thermally modified in thermal modification chamber Katres (Czech Republic).

The Thermowood process took place in three stages: Stage 1 – Heating and drying, Stage 2 – Thermal modification, Stage 3 – Cooling and climatization. The duration of each stage is recorded in Tab. 1.

The samples were placed on metal plates, which were subsequently placed in a thermal modification chamber.

*Tab. 1: Thermal modification process parameters.*

| Thermal modification process | | | |
|---|---|---|---|
| **Parameters** | 160 ° C | 180° C | 210° C |
| Heating (Hours) | 10.6 | 11.4 | 14.6 |
| Thermisation (Hours) | 3.0 | 3.0 | 3.0 |
| Cooling (Hours) | 2.2 | 2.8 | 3.1 |
| **Total modification time** (Hours) | 15.8 | 17.2 | 20.7 |

Before the thermal modification process, the wood was dried at 103°C to 0% moisture content. In this context, the density of the wood sample was also determined (Tab. 2).

The purpose of the dry was to perform the acceleration of the thermal modification process. If the wood for thermal modification is dry, the drying protocol during the thermal modification is shorter.

*Tab. 2. Average density.*

| At the time of testing | | | | |
|---|---|---|---|---|
| **Test samples** | T – 20 | T - 160 | T - 180 | T - 210 |
| **Density ($kg \cdot m^{-3}$)** | 722.1 | 713.2 | 697.1 | 655.4 |
| **Moisture content (%)** | 0 | 0 | 0 | 0 |

The experiment itself was carried out by machining the thermally modified wood on an FVS single-spindle milling machine, which made it possible to precisely adjust the cutting speed. The tool was mounted on a shaft with a diameter of 30 mm. Staton milling heads were used for the machining - fitted with Maximus milling cutters. The angle was chosen because of its most frequent use in practice. In contact with the material, there was always only one pair of knives fitted. The second knife fitted in the milling head only served as a balancing tool.The feed rate was always set using the Maggi Steff feeder.

## Machine parameters:

Power: 5.2 kW, Frequency: 50 Hz, Current system 380/220 (V),number of rotations: 3000, 4500 and 6000, rake angles: 15°, 20° and 25°,cutting speed (vc): 20, 30, 40 $m \cdot s^{-1}$; Manufacturer: Československé hudební nástroje, Type: FVS, Year of manufacture: 1975.The depth of cutting was 1 mm.

## Feed device parameters:

Engine: 400 V, Power: 0.8 – 0.6 kW, Speed: 1400/2800, Feed rate: 4, 8, 11 $m \cdot min^{-1}$, Manufacturer: Maggi, Year of manufacture: 2005.

## Milling head parameters:

Manufacturer: STATON, Year of manufacture: 2004, Tool diameter without knives: 125 mm, Tool diameter including knives: 133 mm, Working tool width: 45 mm, Diameter of clamping hole: 30 mm, Number of knives: 2, Maximum permissible speed: 8000 rpm, Cutter angle: 15, 20, 25°.

## Milling head blade changer parameters:

Manufacturer: Maximus, Type: Special 55, Blade width: 45 (mm), Blade angle (b): 45 (°) (Fig. 3), Material according to ČSN: 19 855, Additives: C 0.7, Cr 4.2; W 18, At 1.5%, Tool hardness: 62 HRC.

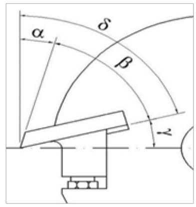


*Fig. 3: Detail of the angle of the cutting knife mounted in the milling head.*

## Methods

Quality of the machined surface – the mean arithmetic deviation values of the waviness profile were determined using the Olympus Lext ols 4100 laser microscope (Fig. 4.), which was placed on thespecial Olymext anti-vibration table.

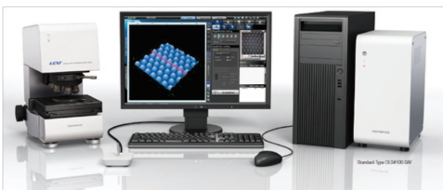

*Fig. 4: OLS 4100*

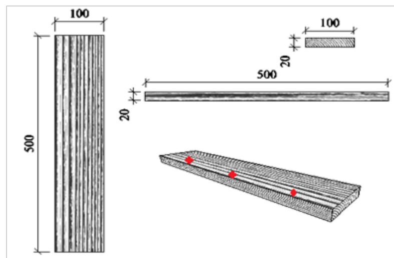


*Fig. 5: Measuring traces.*

Measurement was performed on 108 samples (all combination of variable factors) and on 3 feet of measurement (Fig. 5). This laser microscope operates on a contactless surface scanning principle.

Beforethe measurement, each sample was accurately marked so that the measurements were always carried out in the same place. The measurement was performed on the tangential section. After several test measurements were performed, the „cut-off" values were set according to ISO 4288. Unlike in contact devices, the measurement rate is not set for this type of measuring device. Measurement error is ± 2%.This laser profilometer achieves significantly higher accuracy than other methods such as measuring with a contact-type roughness tester. This is due to the very small radius of the tip of the measuring beam (Fig. 6).

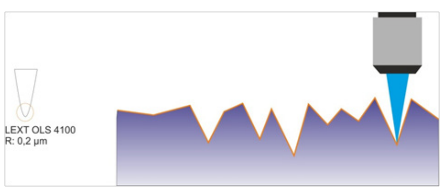


*Fig. 6: Detail of surface scanning.*

The acquired data was recorded and exported to MS Excell in the original Olympus program. We performed the evaluation of the obtained data in Statistica, including all the necessary analyses. To evaluate the measured values, we used a three-factor analysis of variance evaluating the effect of individual factors and the effect of two- and three-factor interactions.

## RESULTS AND DISCUSSION

Tab. 3 shows the average values of the monitored characteristics, values measured for each set of test specimens, and the corresponding coefficient of variation.

*Tab. 3: The effect of individual factors on the monitored characteristic in wood without thermal modification.*

| **Temperature (°C)** | **Cutting speed ($m \cdot s^{-1}$)** | **Angle (°)** | **Feed rate ($m \cdot min^{-1}$)** | **Wa (μm)** |
|---|---|---|---|---|
| 20 | 20 | 15 | 4 | 2.46 (10.7) |
| 20 | 20 | 15 | 8 | 5.02 (11.0) |
| 20 | 20 | 15 | 11 | 6.52 (10.1) |
| 20 | 30 | 15 | 4 | 3.31 (10.1) |
| 20 | 30 | 15 | 8 | 9.43 (5.1) |
| 20 | 30 | 15 | 11 | 6.30 (8.7) |
| 20 | 40 | 15 | 4 | 3.21 (5.9) |
| 20 | 40 | 15 | 8 | 3.65 (3.5) |
| 20 | 40 | 15 | 11 | 3.50 (7.0) |
| 20 | 20 | 20 | 4 | 4.57 (7.6) |
| 20 | 20 | 20 | 8 | 7.54 (6.3) |
| 20 | 20 | 20 | 11 | 8.23 (10.9) |
| 20 | 30 | 20 | 4 | 4.32 (8.9) |
| 20 | 30 | 20 | 8 | 3.55 (11.9) |
| 20 | 30 | 20 | 11 | 4.42 (1.6) |
| 20 | 40 | 20 | 4 | 6.87 (8.0) |
| 20 | 40 | 20 | 8 | 7.65 (6.7) |
| 20 | 40 | 20 | 11 | 4.10 (5.9) |
| 20 | 20 | 25 | 4 | 4.21 (8.9) |
| 20 | 20 | 25 | 8 | 14.93 (16.2) |
| 20 | 20 | 25 | 11 | 7.69 (14.6) |
| 20 | 30 | 25 | 4 | 9.78 (3.9) |
| 20 | 30 | 25 | 8 | 7.77 (13.6) |
| 20 | 30 | 25 | 11 | 4.34 (6.4) |
| 20 | 40 | 25 | 4 | 6.64 (13.4) |
| 20 | 40 | 25 | 8 | 14.47 (9.5) |
| 20 | 40 | 25 | 11 | 7.27 2.7) |

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

Tab. 4 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 160°C, and the corresponding coefficient of variation.

*Tab. 4: The effect of individual factors on the monitored characteristic in wood thermally modified at 160°C.*

| Temperature (°C) | Cutting speed ($m \cdot s^{-1}$) | Angle (°) | Feed rate ($m \cdot min^{-1}$) | Wa (μm) |
|---|---|---|---|---|
| 160 | 20 | 15 | 4 | 4.82 (10.7) |
| 160 | 20 | 15 | 8 | 5.93 (2.5) |
| 160 | 20 | 15 | 11 | 7.32 (5.3) |
| 160 | 30 | 15 | 4 | 6.76 (7.5) |
| 160 | 30 | 15 | 8 | 16.64 (8.8) |
| 160 | 30 | 15 | 11 | 5.50 (8.1) |
| 160 | 40 | 15 | 4 | 8.38 (3.6) |
| 160 | 40 | 15 | 8 | 4.17 (7.6) |
| 160 | 40 | 15 | 11 | 6.97 (12.5) |
| 160 | 20 | 20 | 4 | 6.99 (10.7) |
| 160 | 20 | 20 | 8 | 5.19 (15.3) |
| 160 | 20 | 20 | 11 | 11.33 (17.3) |
| 160 | 30 | 20 | 4 | 4.04 (16.9) |
| 160 | 30 | 20 | 8 | 5.73 (8.4) |
| 160 | 30 | 20 | 11 | 6.79 (5.2) |
| 160 | 40 | 20 | 4 | 5.79 (12.7) |
| 160 | 40 | 20 | 8 | 5.73 (8.2) |
| 160 | 40 | 20 | 11 | 6.48 (7.4) |
| 160 | 20 | 25 | 4 | 3.59 (10.8) |
| 160 | 20 | 25 | 8 | 5.15 (13.5) |
| 160 | 20 | 25 | 11 | 9.51 (14.5) |
| 160 | 30 | 25 | 4 | 7.08 (6.6) |
| 160 | 30 | 25 | 8 | 3.11 (9.4) |
| 160 | 30 | 25 | 11 | 3.79 (12.2) |
| 160 | 40 | 25 | 4 | 4.78 (5.9) |
| 160 | 40 | 25 | 8 | 4.28 (14.7) |
| 160 | 40 | 25 | 11 | 9.94 (12.0) |

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

Tab. 5 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 180°C, and the corresponding coefficient of variation.

*Tab. 5: The effect of individual factors on the monitored characteristic in wood thermally modified at 180°C.*

| Temperature (°C) | Cutting speed ($m \cdot s^{-1}$) | Angle (°) | Feed rate ($m \cdot min^{-1}$) | Wa (μm) |
|---|---|---|---|---|
| 180 | 20 | 15 | 4 | 8.06(15.6) |
| 180 | 20 | 15 | 8 | 6.61(1.5) |
| 180 | 20 | 15 | 11 | 9.10(13.3) |
| 180 | 30 | 15 | 4 | 7.04(6.6) |
| 180 | 30 | 15 | 8 | 4.60(12.5) |

| | | | | |
|---|---|---|---|---|
| 180 | 30 | 15 | 11 | 6.50(3.8) |
| 180 | 40 | 15 | 4 | 7.28(2.7) |
| 180 | 40 | 15 | 8 | 6.31(3.7) |
| 180 | 40 | 15 | 11 | 9.08(5.5) |
| 180 | 20 | 20 | 4 | 5.17(11.8) |
| 180 | 20 | 20 | 8 | 5.23(16.9) |
| 180 | 20 | 20 | 11 | 8.68(17.4) |
| 180 | 30 | 20 | 4 | 6.50(9.7) |
| 180 | 30 | 20 | 8 | 9.63(2.2) |
| 180 | 30 | 20 | 11 | 9.10(12.3) |
| 180 | 40 | 20 | 4 | 4.68(10.5) |
| 180 | 40 | 20 | 8 | 10.56(2.0) |
| 180 | 40 | 20 | 11 | 4.09(13.9) |
| 180 | 20 | 25 | 4 | 3.26(4.2) |
| 180 | 20 | 25 | 8 | 8.70(3.4) |
| 180 | 20 | 25 | 11 | 14.02(5.2) |
| 180 | 30 | 25 | 4 | 4.32(13.7) |
| 180 | 30 | 25 | 8 | 4.91(15.9) |
| 180 | 30 | 25 | 11 | 7.64(9.1) |
| 180 | 40 | 25 | 4 | 4.88(8.9) |
| 180 | 40 | 25 | 8 | 4.79(5.6) |
| 180 | 40 | 25 | 11 | 7.38(16.6) |

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

Tab. 6 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 210°C, and the corresponding coefficient of variation.

*Tab. 6: The effect of individual factors on the monitored characteristic in wood thermally modified at 210°C.*

| **Temperature (°C)** | **Cutting speed ($m \cdot s^{-1}$)** | **Angle (°)** | **Feed rate ($m \cdot min^{-1}$)** | **Wa (μm)** |
|---|---|---|---|---|
| 210 | 20 | 15 | 4 | 12.61 (13.2) |
| 210 | 20 | 15 | 8 | 6.63 (5.2) |
| 210 | 20 | 15 | 11 | 16.44 (1.7) |
| 210 | 30 | 15 | 4 | 14.85 (3.4) |
| 210 | 30 | 15 | 8 | 3.52 (13.1) |
| 210 | 30 | 15 | 11 | 23.56 (8.9) |
| 210 | 40 | 15 | 4 | 4.46 (9.9) |
| 210 | 40 | 15 | 8 | 7.85 (1.8) |
| 210 | 40 | 15 | 11 | 11.79 (10.5) |
| 210 | 20 | 20 | 4 | 5.61 (5.7) |
| 210 | 20 | 20 | 8 | 6.08 (8.6) |
| 210 | 20 | 20 | 11 | 8.90 (5.2) |
| 210 | 30 | 20 | 4 | 3.61 (5.3) |
| 210 | 30 | 20 | 8 | 5.54 (6.5) |

| | | | | |
|---|---|---|---|---|
| 210 | 30 | 20 | 11 | 3.73 (7.0) |
| 210 | 40 | 20 | 4 | 4.39 (13.8) |
| 210 | 40 | 20 | 8 | 6.45 (8.3) |
| 210 | 40 | 20 | 11 | 4.44 (7.3) |
| 210 | 20 | 25 | 4 | 4.38 (6.3) |
| 210 | 20 | 25 | 8 | 13.28 (9.3) |
| 210 | 20 | 25 | 11 | 8.36 (15.7) |
| 210 | 30 | 25 | 4 | 7.68 (15.6) |
| 210 | 30 | 25 | 8 | 14.63 (6.3) |
| 210 | 30 | 25 | 11 | 8.44 (4.5) |
| 210 | 40 | 25 | 4 | 2.92 (1.5) |
| 210 | 40 | 25 | 8 | 8.01 (4.4) |
| 210 | 40 | 25 | 11 | 4.88 (7.6) |

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

Based on the statistical evaluation andthe level of significance "P" shown in Tab. 7 we can state that the effect of individual factors on the mean arithmetic deviation of the waviness profile is statistically significant.

*Tab. 7: Statistical evaluation of the effect of factors and their Interaction on the mean arithmetic deviation of the waviness profile.*

| Monitored factor | Sum of squares | Degree of freedom | Variance | Fisher's F- test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 15991.42 | 1 | 15991.42 | 28061.59 | *** |
| 1) Cutting speed ($m \cdot s^{-1}$) “CS” | 84.39 | 2 | 42.20 | 74.04 | *** |
| 2) Tool's rake angle (°) “TRA” | 131.48 | 2 | 65.74 | 115.36 | *** |
| 3) Feed rate ($m \cdot min^{-1}$) “FR” | 259.36 | 2 | 129.68 | 227.56 | *** |
| 4) Thermal modification °C “TM” | 181.01 | 3 | 60.34 | 105.88 | *** |
| “CS” * “TRA” | 115.37 | 4 | 28.84 | 50.61 | *** |
| “CS” * “FR” | 129.61 | 4 | 32.40 | 56.86 | *** |
| “TRA” * “FR” | 168.22 | 4 | 42.05 | 73.80 | *** |
| “CS” * “TM” | 132.36 | 6 | 22.06 | 38.71 | *** |
| “TRA” * “TM” | 588.33 | 6 | 98.06 | 172.07 | *** |
| “FR” * “TM” | 185.61 | 6 | 30.93 | 54.28 | *** |
| “CS” * “TRA” * “FR” | 188.22 | 8 | 23.53 | 41.29 | *** |
| “CS” * “TRA” * “TM” | 282.96 | 12 | 23.58 | 41.38 | *** |
| “CS” * “TRA” * “TM” | 208.69 | 12 | 17.39 | 30.52 | *** |
| “TRA” * “FR” * “TM” | 795.98 | 12 | 66.33 | 116.40 | *** |
| “CS” * “TRA” * “FR” * “TM” | 471.94 | 24 | 19.66 | 34.51 | *** |
| Error | 123.09 | 216 | 0.57 | | |

NS- not significant, *** - significant

Fig. 7 which shows the effect of the cutting speed on Wa values, indicates that the cutting speed has a statistically significant effect. When the cutting speed increases, the values of the monitored value decrease, i.e. the quality of the surface of the workpiece improves.

Fig. 8 shows the effect of the rake angle on waviness values. The figure shows that the best waviness values were achieved when using a tool with a rake angle of 20°; when using tools with a rake angle of 15° and 25°, similar values of the monitored characteristic were achieved.

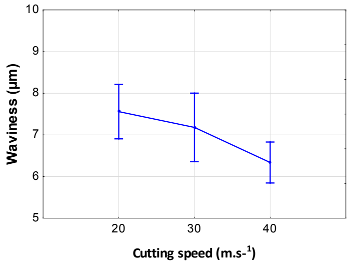


Fig. 7: The effect of the cutting speed on waviness values.

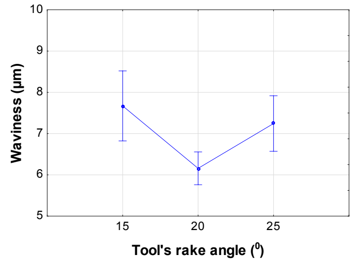


Fig. 8: The effect of the rake angle on waviness values.

Fig. 9 shows the effect of the feed rate on the values of the monitored characteristic. It is evident that the feed rate has the opposite effect of that of the cutting speed, i.e. as the feed rate increases, the mean arithmetic deviation of the waviness profile noticeably increases. The best results were therefore achieved at a feed rate of 4 $m \cdot min^{-1}$.

The effect of thermal modification is shown in Fig. 10. When using thermally modified wood, the values of the monitored characteristic always deteriorate. The higher the degree of thermal modification, the worse the values of the monitored characteristic. Upon increasing, the temperature of the thermal modification there is a loss of matter due to the chemical reactions that take place at an elevated temperature. See Tab. 2 where it is obvious that the density decreases with increasing temperature of the thermal modification. This effect partly affects the resulting waviness.

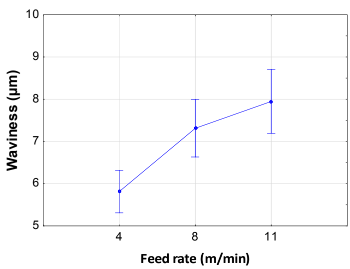


Fig. 9: The effect of the feed rate on waviness values.

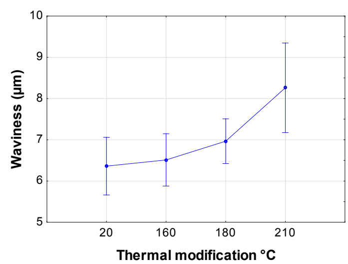


Fig. 10: The effect of thermal modification on waviness values.

The comparison of the effect of individual factors is in Tab. 8.

*Tab. 8: Comparison of the effects of individual factors using Duncan'stest on the Wa values with a laser profilometer.*

| **Cutting speed ($m \cdot s^{-1}$)** | | **(1) 7.5585** | **(2) 7.1802** | **(3) 6.3375** |
|---|---|---|---|---|
| 1 | 20 | | 0.000 | 0.000 |
| 2 | 30 | 0.000 | | 0.000 |
| 3 | 40 | 0.000 | 0.000 | |
| **Tool's rake angle (0)** | | **(1) 7.6722** | **(2) 6.1589** | **(3) 7.2451** |
| 1 | 15 | | 0.000 | 0.000 |
| 2 | 20 | 0.000 | | 0.000 |
| 3 | 25 | 0.000 | 0.000 | |
| **Feed rate ($m \cdot min^{-1}$)** | | **(1) 5.8146** | **(2) 7.3128** | **(3) 7.9488** |
| 1 | 4 | | 0.000 | 0.000 |
| 2 | 8 | 0.000 | | 0.000 |
| 3 | 11 | 0.000 | 0.000 | |

| **Thermal modification °C** | | **(1) 6.3615** | **(2) 6.5122** | **(3) 6.9667** | **(4) 8.2612** |
|---|---|---|---|---|---|
| 1 | 20 | | 0.204 | 0.000 | 0.000 |
| 2 | 160 | 0.204 | | 0.000 | 0.000 |
| 3 | 180 | 0.000 | 0.000 | | 0.000 |
| 4 | 210 | 0.000 | 0.000 | 0.000 | |

Fig. 11 shows the effect of individual rake angles, feed rates and cutting speeds on the values of the monitored characteristic for oak wood without thermal treatment.

Fig. 12 shows the effect of individual rake angles, feed rates and cutting speeds on the mean arithmetic deviation of the waviness profile for oak wood thermally modified at 160°C.

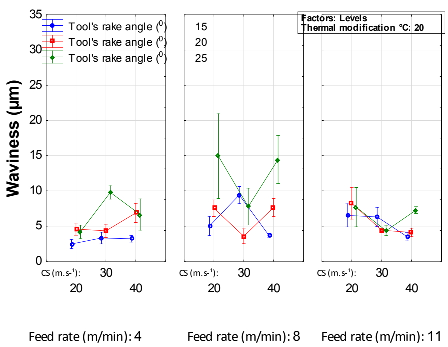


*Fig. 11: Synergistic effect of the studied factors on the Wa in wood without thermal treatment.*

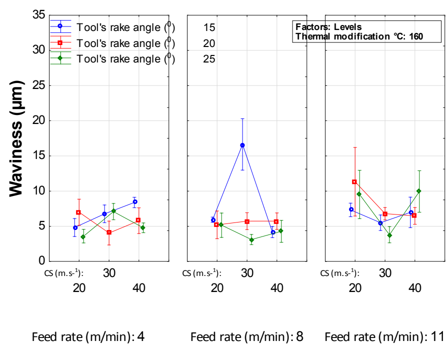


*Fig. 12: Synergistic effect of the studied factors on the Wa in wood thermally modified at 160°C.*

Fig. 13 shows the effect of individual rake angles, feed rates and cutting speeds on the mean arithmetic deviation of the waviness profile for oak wood thermally modified at 180°C.

Fig. 14 shows the effect of individual rake angles, feed rates and cutting speeds on the mean arithmetic deviation of the waviness profile for oak wood thermally modified at 210°C.

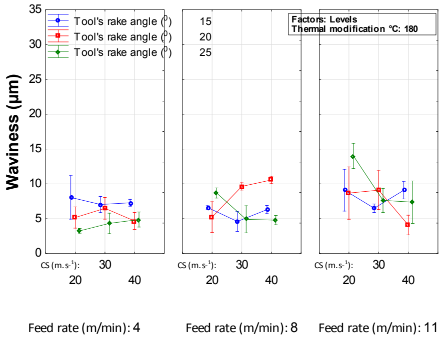


*Fig. 13: Synergistic effect of the studied factors on the Wa in wood thermally modified at 180°C.*

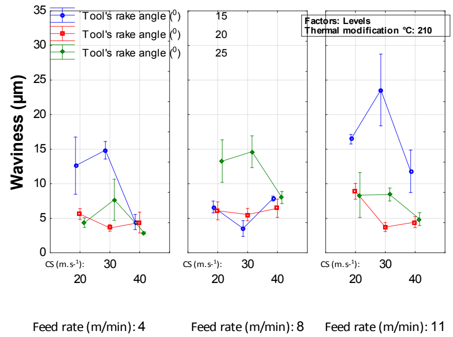


*Fig. 14: Synergistic effect of the studied factors on the Wa in wood thermally modified at 210°C.*

We dealt with the issue of the quality of the machined surface in the article (Kvietková et al. 2015d). When comparing the results, we can conclude that the observed trends of the effect of individual parameters on oak wood and birch wood are confirmed.

Mazáň et al (2016) who focused on examining pine wood in the article, and published the results of the research on the effect of tool geometry and thermal modification on the surface quality, reached similar conclusions on the effect of thermal modification. We can therefore state that when thermally modified wood is machined, the quality of the machined surface deteriorates. Similar conclusions are also published by Budakçı et al. (2011, 2013).

Costes and Larricq (2002) also found that the cutting speed has a significant effect on the quality of the machined surface. Škaljić et al. (2009) stated that as the cutting speed increases, the quality of the machined surface declines; our research confirms this in oak wood without and with thermal modification.

## CONCLUSIONS

1. The feed rate has proven to be an important factor in the process of machining thermally modified wood. When the feed rate is increased, the surface quality deteriorates. The best values were measured at a feed rate of 4 m·min$^{-1}$.
2. The cutting speed has an opposite effect on the values of the mean arithmetic deviation of the waviness profile. As the cutting speed increases, better values of the monitored characteristic are achieved. The quality of the surface was the best at a cutting speed of 40 m·s$^{-1}$.
3. The effect of thermal modification on the mean arithmetic deviation of the waviness profile was clearly proven. When oak wood is thermally modified at a temperature in the range of 160°C – 210°C, the values of the monitored characteristic deteriorate. As the degree of thermal modification increases, the waviness values worsen.
4. We can also improve the mean arithmetic deviation of the waviness profile by using a tool with the right rake angle. We found that a tool with a rake angle of 20° is the most suitable for machining oak wood.

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