Surface roughness investigation of CNC pocket milling of hardwood beech

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ABSTRACT

The paper purpose is to investigate the influence of some of the machining input factors and conditions on the surface texture and roughness parameters. The machining tests were carried out on a homebuilt (DIY) CNC router with a one teeth carbide flat end mills. The router movements were calibrated in order to assure three decimals precision. The spindle speed is controlled by a frequency converter that allows setting the speed ranging from 0 to 20000 rpm. Rectangular pockets were milled considering cutting across and along the grain and at a 45-degree angle. Different cutting path strategies were generated using a specialized CAM software. A Taguchi DOE method was considered and a confocal microscope type CWM 100 produced by Mahr was used to analyze the surface texture and roughness parameters .

Keywords:

CNC machining, cutting strategy, beech wood, surface quality

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INTRODUCTION

Hardwood, such as beech, is often used in the construction or furniture industry to make various decorative elements, offering great resistance in operation but also refinement. This requires special attention to the details of the processing. In order to increase productivity and reduce production costs, the machining process can be carried out on CNC machines. Those equipment's are quite affordable today, offering the possibility to quickly generate complex surfaces with a much higher surface quality and dimensional accuracy compared to traditional methods. On these equipment's, the main manufacturing operation is milling, where different types of cutters can be used, and in some cases, depending on the specifics of the cutting regime, finishing can be suppressed. Anyway, regardless of the type of cutter used, vibrations occur during processing that affect the quality of the surface. In this regard, topical studies undertaken in [1-5], highlight the influence of the different parameters of the cutting regime. In a preliminary study [6] the parameters of the cutting regime were evaluated and a dependence of the roughness on the direction of the grain in beech wood was established. or this reason, in the present work, a series of parameters of the cutting regime are analyzed, such as: speed, feed, direction of the respective grain and the path of the tool. The study aims to establish the influence of the input of each of these parameters on the roughness through an optical analysis on the confocal microscope. For this, rectangular pockets were made based on a complete Taguchi DOE plan.

The used CNC is a homebuilt (DIY) router. Based on the information from [7] and [8], where the performances of these types of CNCs are analyzed, thick aluminum sheet frames were used in CNC construction, to ensure greater rigidity, precision guide elements were also used and 57BYGH115-003 stepper motors with 200-pole for increased precision. The calibration of the CNC router for each individual axis was carried out using a digital dial gauge with 1µm accuracy. The cutting tool used is a single tooth milling cutter made of metal carbide AK44 and the tip diameter of 2.5mm .

Experimental setup

All experimental investigations were performed on a CNC DYI router shown in Figure 1. Its base is made of a solid aluminum frame, which in turn includes stepper motors (4), and a 1.5kW air-cooled spindle motor (1), used to drive the tool (11), as well as a worktable in the form of an MDF plate (9) which helps to fix the workpiece using a fixing device (10). The axial motions of the tool are obtained by means of ball screws (5), linear bearings (7) and precision rods (6). Tools (2) up to Φ8 mm can be used and the spindle is controlled by a computer (12) and a frequency converter (13) .

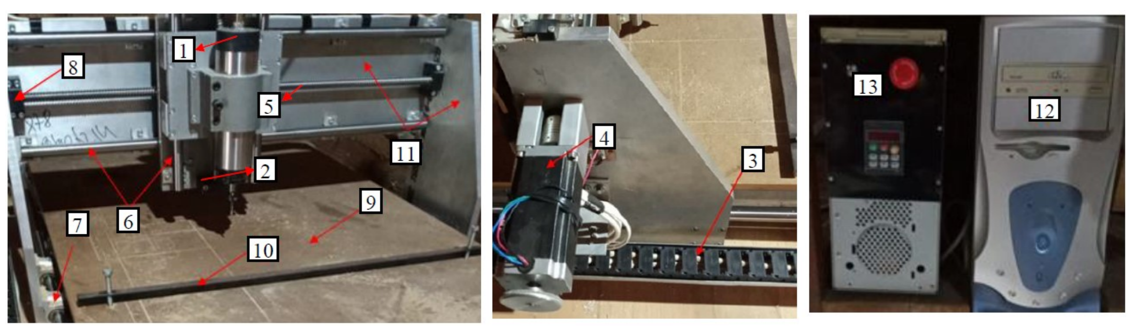


Fig. 1 CNC router overview

As previously mentioned, the study of the influence of the specified parameters was carried out according to the DOE Taguchi L27 experimental design (Table 1), customized for four input parameters at three levels of variations. The cutting tool geometry is presented in figure 2 c. The tool paths were generated using the Manufacturing module of the Siemens NX software. Three cutting strategies were considered: follow profile (the tool paths follow the profile of the rectangular cavity), zig-zag (linear paths parallel with one of the rectangular cavity wall with a series of short sharp turns) and zig (linear path parallel with a rectangular cavity wall distanced by the step overs). Helical engaged strategy was used for all the experiments carried out. The stepover value was set at 25% of the tool diameter in order to assure proper tool loads .

Table 1. Taguchi L27 DOE.

Nr.	Direction, D [°]	Spindle speed, n [mm/rev]	Cutting strategy, CT	Feed, f [mm/s]	Roughness, Ra [µm]
1	0	10000	1	300	1.139
2	0	10000	2	550	1.293
3	0	10000	3	800	0.741
4	0	15000	1	550	0.544
5	0	15000	2	800	1.127
6	0	15000	3	300	0.613
7	0	17000	1	800	0.879
8	0	17000	2	300	0.549
9	0	17000	3	550	0.611
10	90	10000	1	550	0.540
11	90	10000	2	800	0.612
12	90	10000	3	300	0.541
13	90	15000	1	800	0.664
14	90	15000	2	300	0.467
15	90	15000	3	550	0.593
16	90	17000	1	300	0.501
17	90	17000	2	550	0.362
18	90	17000	3	800	0.480
19	45	10000	1	800	1.160
20	45	10000	2	300	0.855
21	45	10000	3	550	0.839
22	45	15000	1	300	0.567
23	45	15000	2	550	0.691
24	45	15000	3	800	1.082
25	45	17000	1	550	0.457
26	45	17000	2	800	0.723
27	45	17000	3	300	0.650

The experimental determinations for the levels of variation considered for machining in the grain direction, D, were carried out as shown in Figure 2. The rectangular pockets were milled considering cutting across (90°), along the grain (0°) and at a 45-degree angle of inclination.

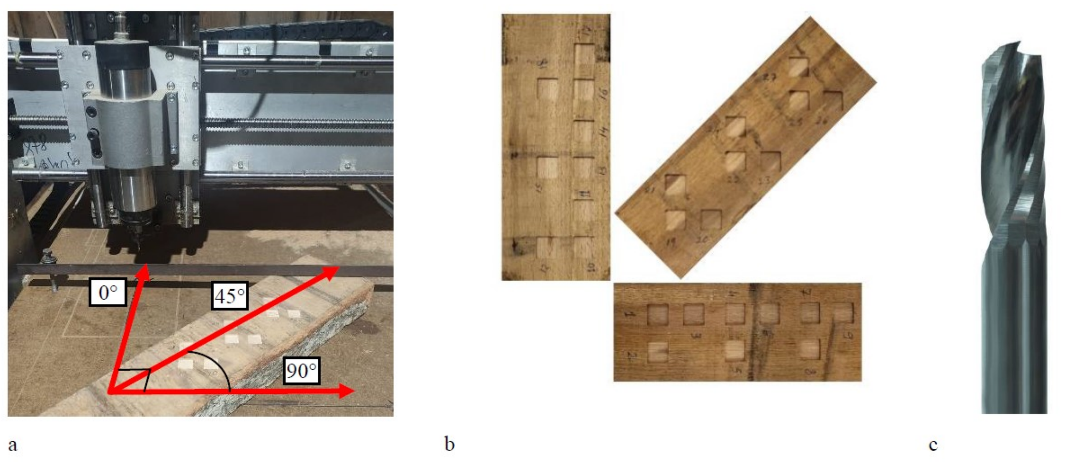


Fig. 2. Grain direction

The cutting path strategies were generated using a specialized CAM software, and are related to the specifications in Table 1 as follows: 1. - Follow profile Figure 3.a); 2. - Zig-Zag in Figure 3.b) and 3. - Zig Figure 3.c).

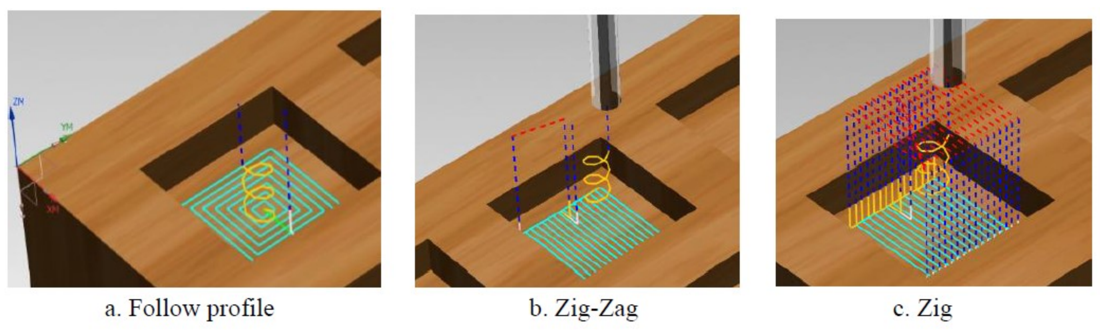


Fig. 3. Pocket milling path strategies

The surface roughness obtained from the experimental determinations was analyzed using a Mahr CWM 100 confocal microscope presented in Figure 4. Using MountainsLab software, it was possible to obtain roughness values and 3D images of the machined surface microtopography.

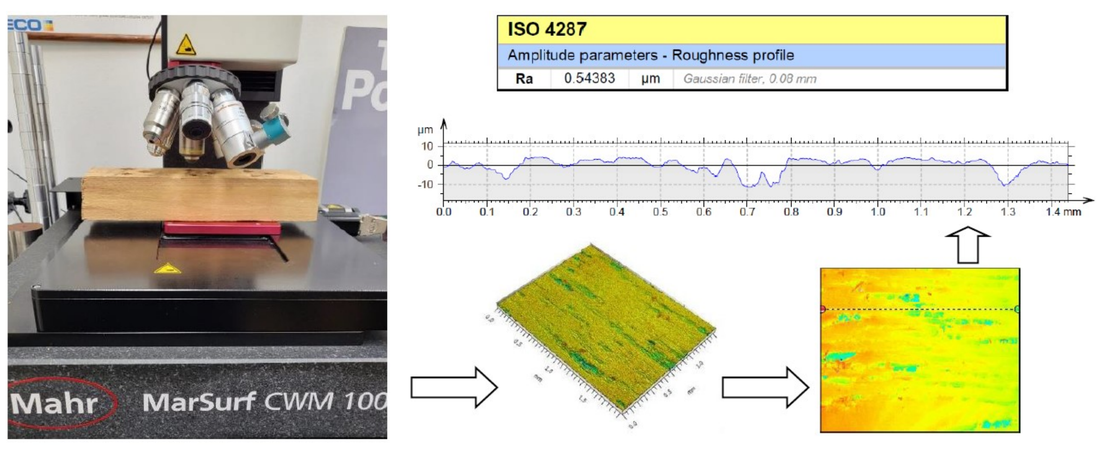


Fig. 4. Surface quality study and roughness value

Results and discutions

The experimental data was processed using a DOE specialized software Minitab free trial. By using the Taguchi DOE design, the Main Effects variation graphs from Figure 5.a) has been achieved. Also, in the Figure 6 an analysis of the influence between the cutting direction and the other main factors of the process, proposed for this study was made. Analysis of variance (ANOVA), allowed the plotting of the Pareto chart in the Figure 5.b), where the ranking of the influence of each factor studied can be observed, for a significance level (denoted by α) set apriori by the researcher. Usually, in engineering calculations, this significance level is set for a maximum risk of 5%. When the Fisher test value (P-Value) is less than the significance level (0.05 in our case), it means that the factor is statistically significant. As it can be seen, the wood grain direction is statistically significant, followed by the cutting speed the and cutting feed while the cutting strategy shows the lowest significance. The differences between the factors can be corelated between Figure 5.a and b to cofirm the variation. Table 2 sumarises the variation degree and the significance of every studied factor.

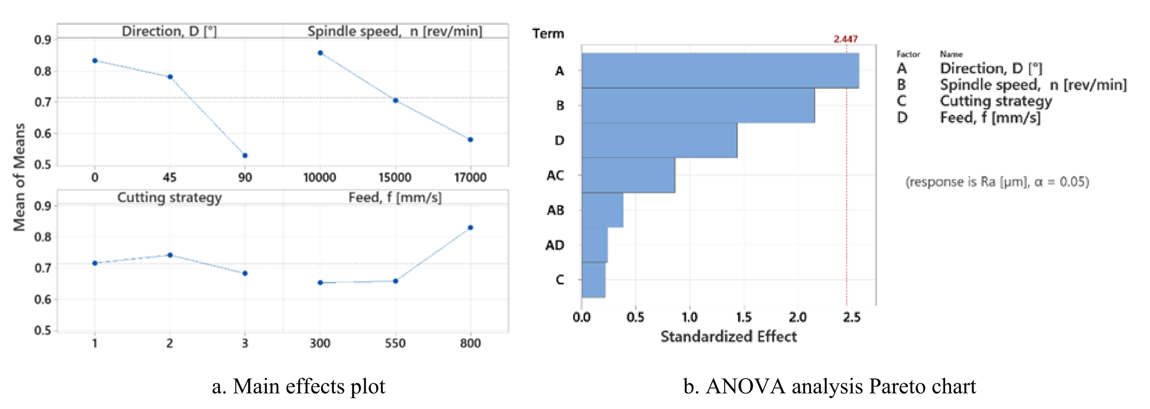


Figure 5. Main effects plot and Pareto chart

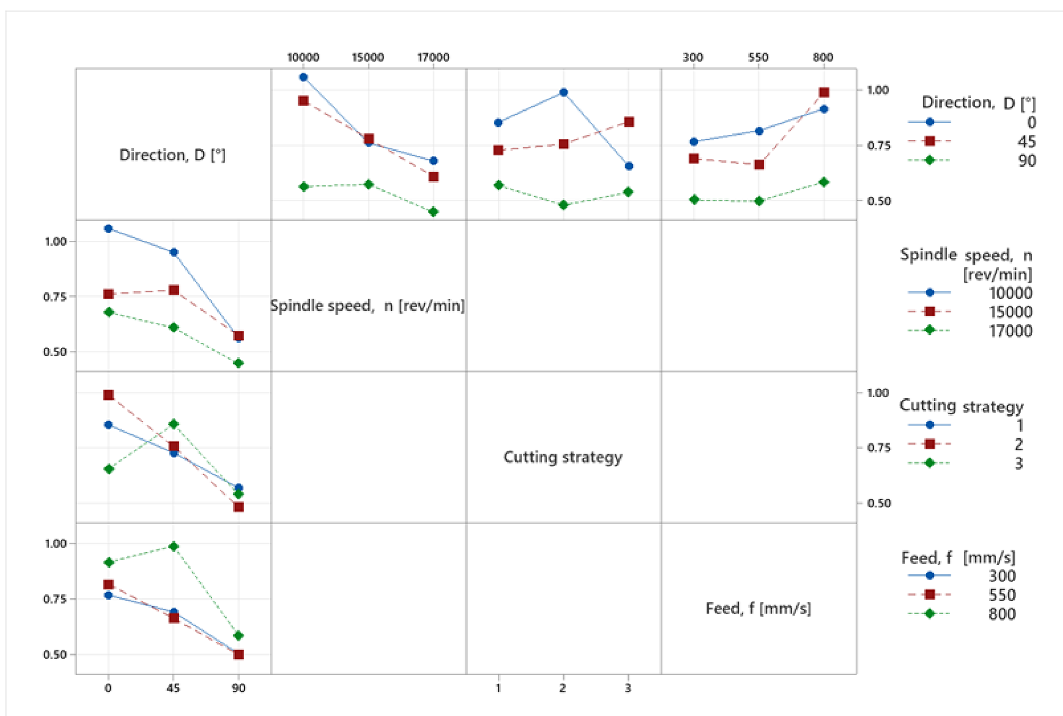


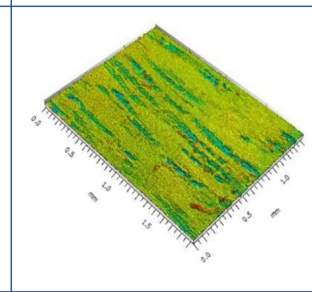
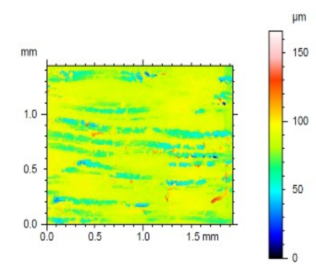
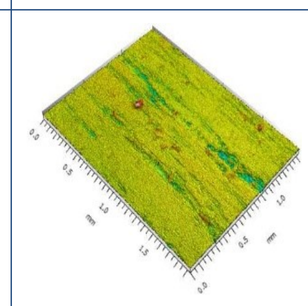
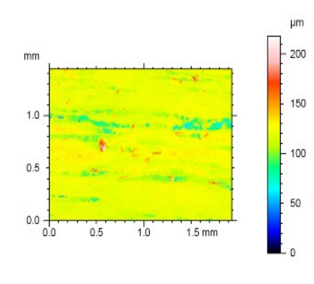
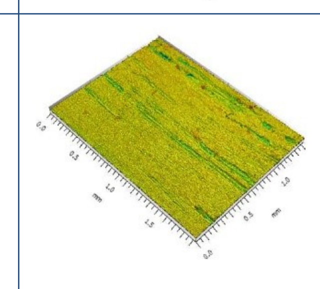
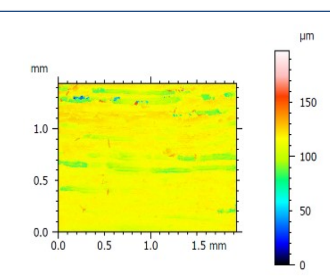
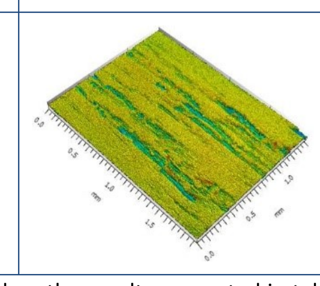
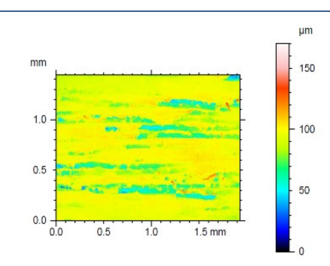
Figure 6. Interaction plot

Table 2. Variation and significance degree of the studied factors.

Level	Direction, D [°]	Spindle speed, n [mm/rev]	Cutting strategy, CT	Feed rate, f [mm/s]
1	-	-	-	-
2	↓ 6.31%	↓ 17.77%	↑ 3.56%	↑ 0.81%
3	↓ 32.24%	↓ 17.9%	↓ 7.92%	↑ 25.94%
1	-	-	-	-
3	↓ 36.52%	↓ 32.48%	↓ 4.65%	↑ 26.96%
Signifiance percent				
-	40.27%	33.78%	22.56%	3.38%

Analyzing the results, in the case of grain direction, it can be seen a roughness improvement with about 6.31%, compared to the first level, followed by 32.24%. Between the first level and the third level there is a roughness improvement by about 36.5%. Same goes for the cutting speed. By using higher spindle speeds, the roughness improves with a total of 32.48%. The cutting strategy, even though it is a categorical variable, presents a 8% roughness improvement when using zig – zag strategy compared the the other two. The feed rate influences the roughness values in a negative way.

Table 3. Obtained surfaces .

Taguchi	3D	2D	Taguchi Values
7			0° n: 17000 [mm/rev] follow periphery f: 800 [mm/s]
8			0° n: 17000 [mm/rev] zig f: 300 [mm/s]
15			90° n: 15000 [mm/rev] zig-zag f: 550 [mm/s]
24			45° n: 17000 [mm/rev] zig-zag f: 800 [mm/s]

Based on the results presented in table 3, it was observed that at high feed rate values, the pulling of the grains occurred more pronounced than when low values were used. Another phenomenon consists in the appearance of non-detached chips. In the same way, depending on the direction of the grain, the surfaces with fewer cavities produced by pulling out the grains were obtained in the case of machining in the perpendicular direction (90°) .

Conclusions

For the machining conditions considered the values obtained for the surface roughness, Ra parameter ranged between 0.36 µm and 1.29 µm, values that correspond to finishing processes.

It was found that, in the case of machining in the direction parallel to the grain, the average value obtained is 0.83 µm, and in the case of machining at an angle of 45°, the average roughness obtained is close to the case of machining at 0°, being 0.78 µm. In the case of machining perpendicular to the grain, a considerable improvement of the surface quality from a geometrical point of view was observed, the average roughness being 0.53 µm, which means an improvement of about 36% compared to machining at 0° and 32% compared to machining at 45°.

From the all studied factors, ANOVA analysis showed that the biggest influence on surface roughness has the grain direction, followed by the cutting regime, in particular the cutting speed, while the cutting strategy had the lowest impact on roughness values. Also, from the analysis, it was observed that the interaction between the grain direction and cutting strategy had a relatively average significance compared with other interactions. This phenomenon can be explained that by using different types of strategies, the actual direction of the wood grain, relative to the tool position, changes. Based on the analyzed results, the regression function was deduced with the Minitab software in the form of relation 1. Due to the fact that the CT factor is qualitative, it can only be assigned the values 1, 2 or 3 according to the notations from the table 1.

$$R_a = 1.238 - 0.003380 \cdot D - 0.000038 \cdot n - 0.0167 \cdot CT + 0.000352 \cdot f \quad [\mu m] \qquad (1)$$

The 3D images revealed that at higher feed rates, the cavities produced by the grain pull-out are larger and more frequent, resulting in higher roughness values. The same phenomenon can be observed when the machining direction is parallel or oblique to the grain, a small number of cavities being recorded during perpendicular machining.

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