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OPTIMIZATION OF THE CNC MILLING PROCESS VIA MODIFYING SOME PARAMETERS OF THE CUTTING MODE WHEN PROCESSING MDF WORKPIECES

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ABSTRACT

The modification in the surface quality of Medium Density Fiberboard (MDF) workpieces machined in a CNC milling machine is investigated in the paper. The quality of the milling process is affected by the surface roughness. The present work is focused on the influence of the following cutting parameters: rotation speed (*n*), feed rate (V_f) and radial depth of cut (*h*) in optimising the milling process and improving the quality of the milling surface. The roughness of the processed surfaces was measured with a roughness tester, type "Surftest SJ-210" (Mitutoyo, Japan). The surface quality is evaluated using the defined average arithmetical values of roughness parameters $\overline{R_z}$. The results of the current study showed the following optimal values of the variable factors that ensured the highest quality of the processed surface: rotation n = 18000 min^{-1}, feed rate V_f = 3.5 m.min^{-1} and radial depth of cut h = 3 mm. Based on the experiments performed, graphical dependencies, presenting the influence of the individual factors on the quality of the processed surface were derived.

Keywords: surface quality; CNC-machining center; cutting mode; CNC shank cutter; MDF; rotation speed; feed rate.

INTRODUCTION

The processing of wood and wood-based materials by milling is one of the most frequently used technological operations aimed at giving a certain shape and roughness to the processed surfaces.

CNC-machining centers are increasingly used in modern furniture production. They are characterized by several advantages, among others, ensuring a higher quality of the treated surface.

The influence of various factors on the quality of the milled surface has been studied by a few authors related to the characteristics of the cutting tool, the cutting modes in which the materials are processed and its characteristics. In recent years, a number of studies investigated the influence of different factors, e.g., cutting and feeding speeds, cutting forces, degree of wear of the tool, vibrations on the quality of the processed surface (Ohuchi and Murase 2001, Ohuchi and Murase 2006, Ohuchi *et al.,* 2008, Davim *et al.,* 2009, Sedlecký *et al.,* 2018).

In their research, Davim *et al.* (2009) and Sedlecký *et al.* (2018) showed that the roughness values of the processed surfaces of MDF workpieces decrease with an increase in the rotation speed and a decrease in the feed rate. These results were confirmed by the results of other authors (Kminiak *et al.,* 2017; Deus *et al.,* 2015; Vitchev and Gochev 2018). In one of their publications, Aguilera *et al.* (2000) investigated the roughness of milled MDF workpieces with different densities. They concluded that a deterioration in the quality of the milled surface was observed at a higher density of MDF. The surface roughness is also influenced by the characteristics and design of the cutting tools (Curti *et al.,* 2017; Sedlecký 2017; Vitchev 2019).

Most of the factors affecting the milling process can be controlled and managed. Therefore, their influence on the surface roughness should be studied, in order to apply optimal milling modes.

The objective of this study was to investigate the influence of the following factors: rotation speed (n), feed rate (V_f) and radial depth of cut (h) on the surface quality of MDF workpieces processed with CNC-machining center.

MATERIALS AND METHODS

The experimental research was performed with a CNC-machining center, model Rover A 3.30 (Biesse, Italy) (Figure 1). The machine has three interpolated control axes (X, Y and Z), with operational steps of X = 3060 mm; Y = 1260; mm; Z = 150 mm, correspondingly. The machine software provides the opportunity for stepless regulation of feed rate (V_f) and change of cutting speed via changing the rotation speed (n).

Fig. 1 General appearance of CNC-machining center, model A 3.30 (Biesse, Italy).

For the cutting process a new CNC finishing spiral router cutter, with a negative spiral with sharpening radius ρ_0 = 6 µm, made from solid tungsten carbide (CMT, Italy, figure 2) was used. The technical characteristics of the cutting instrument are presented in table 1, where: D is the cutting circle diameter, I – the cutting length, L – the total length, s – the diameter of the shank, z – the number of spirals (number of teeth), n – maximum RPM.

Fig. 2 CNC shank spiral finishing cutter – CMT (Italy).

Tab. 1 Technical characteristics of the utilized instrument.

D **mm**	***I*** **mm**	***L*** **mm**	***d*** **mm**	***Z*** **count**	***n*** **min^{-1}**	**Material of the teeth**	**Geometry**
12	35	83	12	3	18000	Solid tungsten carbide	Negative spiral

For the purpose of the experiment, unfinished MDF workpieces, were used. The processed details were with the following dimensions: length (*L*) x width (*B*) x thickness (*T*) = 1000 x 200 x 18 mm. The details were processed longitudinally along their edge. The fibreboards were maintained at a temperature of 20 °C ± 3 °C and the methodology for density determination is in accordance with BDS EN 323 and was performed in the laboratory of Kastamonou, Bulgaria. The measured average density amounts to 740 $kg.m^{-3}$.

To evaluate the influence of the factors: rotation speed of shank cutter (*n*), feed rate (V_f) and radial depth of cut (*h*), the methodology of multifactorial planning (Vuchkov 1986) was implemented. The levels of variation in the variable factors are presented clearly and in coded mode in Table 2.

Tab. 2 Levels of variable factor's change *n*, V_f and *h*.

Variable factors	**Minimum value**		**Average value**		**Maximum value**	
	expl.	**coded**	**expl.**	**coded**	**expl.**	**coded**
Rotation speed $n = X_1$ [min^{-1}]	12000	-1	15000	0	18000	1
Feed rate $V_f = X_2$ [$m.min^{-1}$]	2	-1	3.5	0	5	1
Radial depth of cut $h = X_3$ [mm]	1	-1	2	0	3	1

The quality of the processed surface, depending on the variable factors, was evaluated by the roughness parameter R_z. It was defined for each base length of the studied surface area. The methodology to determine the surface roughness is in accordance with the BDS EN ISO 4287 and was also described by Gochev (2005). The roughness measurements were carried out along the MDF cross section at both ends and at the center of the sample.

The values of the roughness parameters were measured with a portable roughness tester, model Surftest SJ-210 (Mitutoyo, Japan) (Figure 3), with a reverse travel sensor and a diamond, *V*-shaped probe tip with radius *R* = 5 μm, according to BDS EN ISO 3274:2002, in the following settings:

- profile – R, profile filter – Gauss;
- number of base lengths $n_1 = 5$;
- evaluation length ln =12.5 mm;
- upper limit of filter λc = 2.5 mm;
- lower filter limit λs = 8 μm;
- measuring speed 0.25 mm.s^{-1}.

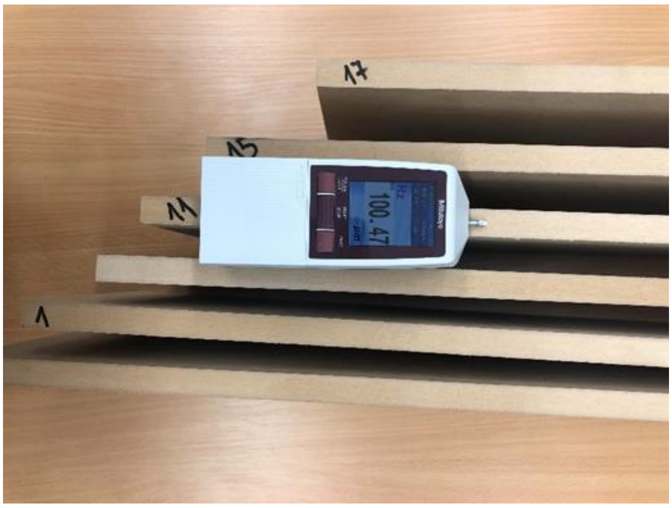

Fig. 3 General appearance of the a portable measuring instrument for surface roughness, model Surftest SJ-210.

The data were statistically analysed by a specialized software Q-StatLab.

RESULTS AND DISCUSSION

Based on the performed experiments and the mathematical analysis of the results, the following regression equation was derived (1):

$$y = 93{,}190 + 0{,}239X_1 + 8{,}174X_2 - 9{,}171X_3 - 2{,}364X_1^2 + 5{,}351X_2^2 - 3{,}324X_3^2 - 0{,}076X_1X_2 + 2{,}634X_2X_3 - 2{,}809X_1X_3 \quad (1)$$

Where:
y – predicted value of the output value, defined by the roughness parameter Rz coded.
X_1 – rotation speed (n) coded.
X_2 – feed rate (V_f) coded.
X_3 – radial depth of cut (h) coded.

Using the derived regression equation (1), numerically, the variation of the roughness parameter R_z can be predicted, depending on the values of the variable factors: rotation speed ($n = X_1$); feed rate ($V_f = X_2$); radial depth of cut ($h = X_3$).

Table 3 presents the experimental matrix, on the basis of which the combinations of the studied parameters and their levels of variation were established, and the experimental study was carried out. The calculated arithmetic average values of the roughness parameter $\overline{R_z}$ (μm) are also presented in Table 3. After performing the statistical and mathematical analysis, the regression coefficients were derived and presented in Table 4.

Tab. 3 Planning matrix for three-factorial experiments and average values of the roughness parameter $\overline{R_z}$ (μm).

№	$X_1 = n$ min^{-1}		$X_2 = V_f$ m.min^{-1}		$X_3 = h$ mm		$\overline{R_z}$ μm	№	$X_1 = n$ min^{-1}		$X_2 = V_f$ m.min^{-1}		$X_3 = h$ mm		$\overline{R_z}$ μm
1	-1	12000	-1	2	-1	1	94.20	9	-1	12000	0	3.5	0	2	94.31
2	-1	12000	-1	2	1	3	75.28	10	1	18000	0	3.5	0	2	86.69
3	-1	12000	1	5	-1	1	100.47	11	0	15000	-1	2	0	2	84.82
4	-1	12000	1	5	1	3	9.79	12	0	15000	1	5	0	2	111.61
5	1	18000	-1	2	-1	1	100.12	13	0	15000	0	3.5	-1	1	101.56
6	1	18000	-1	2	1	3	74.67	14	0	15000	0	3.5	1	3	77.52
7	1	18000	1	5	-1	1	110.79	15	0	15000	0	3.5	0	2	89.08
8	1	18000	1	5	1	3	91.17								

Tab. 4 Regression coefficients.

Coefficient	Coded value	Coefficient	Coded value	Coefficient	Coded value
b_1	0.239	b_{11}	-2.364	b_{12}	-0.076
b_2	8.174	b_{22}	5.351	b_{23}	2.634
b_3	-9.171	b_{33}	-3.324	b_{13}	-2.809

From the values of the regression coefficients, it is visible that the most significant influence on the roughness parameter had the feed rate (V_f), with regression coefficient b_2 = 8.174, followed by the rotation speed of the shank cutter (n), with regression coefficient b_1 = 0.239.

The changes in the roughness parameter R_z depending on the rotation speed (n) and the feed rate (V_f), are presented in Figure 4. The obtained results showed that at the two lower feed rates V_f = 2 m.min^{-1} and V_f = 3,5 m.min^{-1}, the roughness changed from 81 μm to 93 μm. Higher values of the roughness parameter R_z could be observed with the rotation speed of the shank cutter as follows: at n = 15000 min^{-1} and V_f = 2 m.min^{-1}, R_z = 90 μm; at n = 15000 min^{-1} and V_f = 3,5 m.min^{-1}, R_z = 93 μm. Based on the roughness graphs for the three feed rates it is visible that the highest roughness of the processed surfaces is measured at feed rate of V_f = 5 m.min^{-1}, whereas the parameter value R_z changes within 104 μm to 106,7 μm. An increase in the rotation speed of the shank cutter results in insignificant deterioration of surface quality at every parabola in between the initial, peak and end value of R_z (Figure 4).

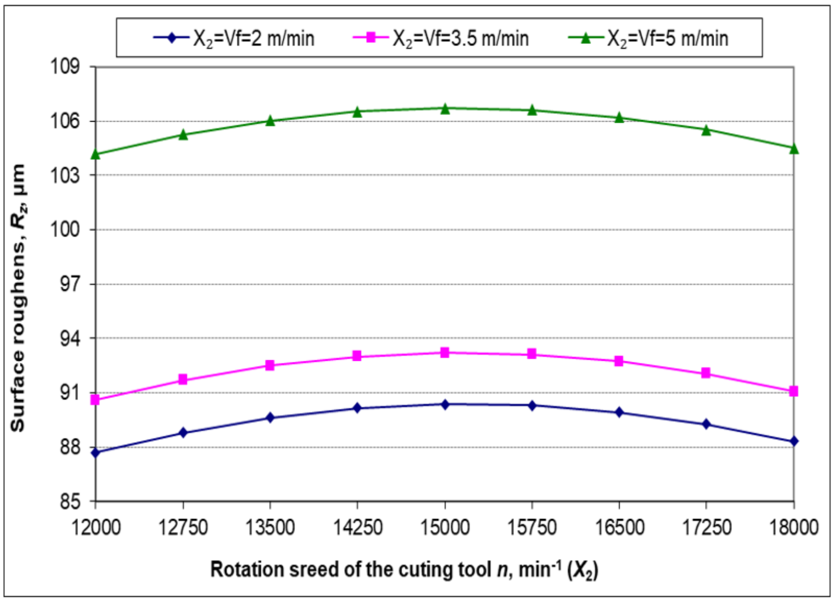

Fig. 4 Modification of the roughness parameter R_z depending on the rotation speed of the shank cutter (n) and the feed rate (V_f).

The correlation between the rotation speed of the shank cutter (*n*) and the radial depth of the cut (*h*) is presented in Figure 5. The results showed that the best quality of the processed surfaces is achieved with the rotation speed of the shank cutter n = 18000 min^{-1} and radial depth of cut h = 3 mm. Similar results were reported by Deus et al. (2015) and İşleyen (2019). Their research showed that the roughness of MDF workpieces decreased by increasing the rotation speed of the cutting tool and the depth of cut.

A decrease in the radial depth of cut below 3 mm (h = 2 mm; h = 1 mm) resulted in an increase in the roughness of the processed surfaces. This could be due to the increased vibration in the contact area between the processed detail and the cut-off layer. This relationship is most pronounced in the thinnest radial depth of cut (h = 1 mm), where the roughness also increases with the increase of the rotation speed of the shank cutter (*n*) within the studied range (Figure 5). These results support the assumption that increased roughness is a result of the increased vibrations generated by the increased rotation speed of the shank cutter and at the same time could not be compensated by the smaller radial depth of cut.

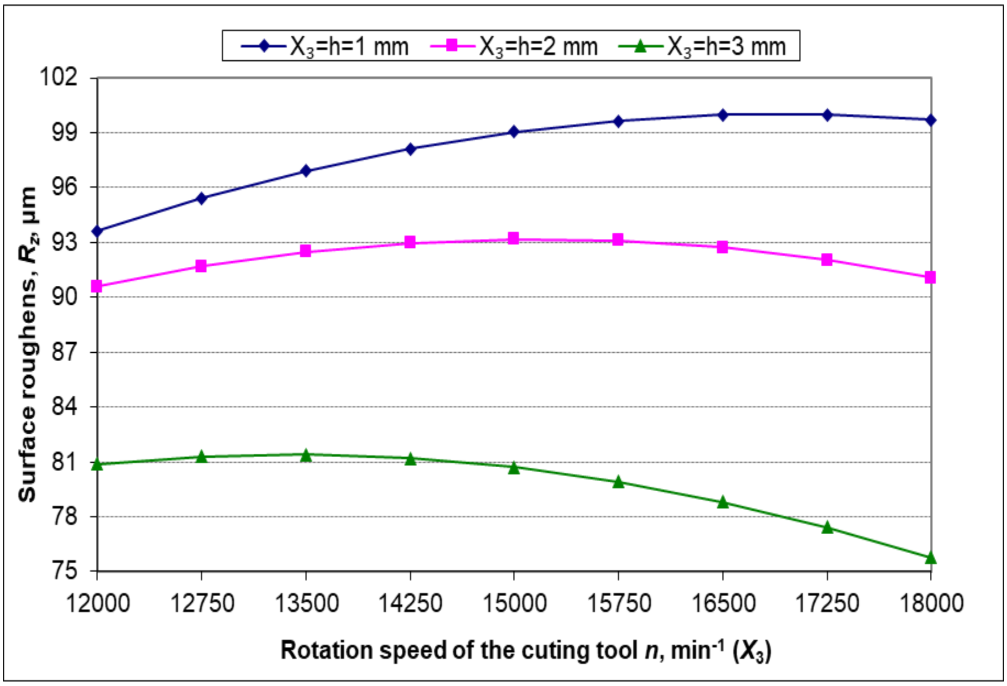

Fig. 5 Modification of the roughness parameter *Rz* depending on the rotation speed of the shank cutter (*n*) and radial depth of cut (*h*)

The correlation between the feed rate (V_f) and radial depth of cut (*h*) is presented in Figure 6. The curves depict the impact of the feed rate (V_f), on the quality of processed surfaces (R_z). The results clearly show that with an increase in the feed rate, the roughness of the processed surfaces increases as well. Also here, it is visible that an increase is most pronounced in the thinnest radial depth of cut h = 1 mm (Figure 6). The strong influence of the feed rate (V_f) on the roughness of the process surface is also reported by other authors (Kminiak *et al.,* 2020, Sedlecký 2017, Sedlecký *et al.,* 2018, Ohuchi *et al.,* 2008, Ohuchi and Murase 2006, Ohuchi and Murase 2001).

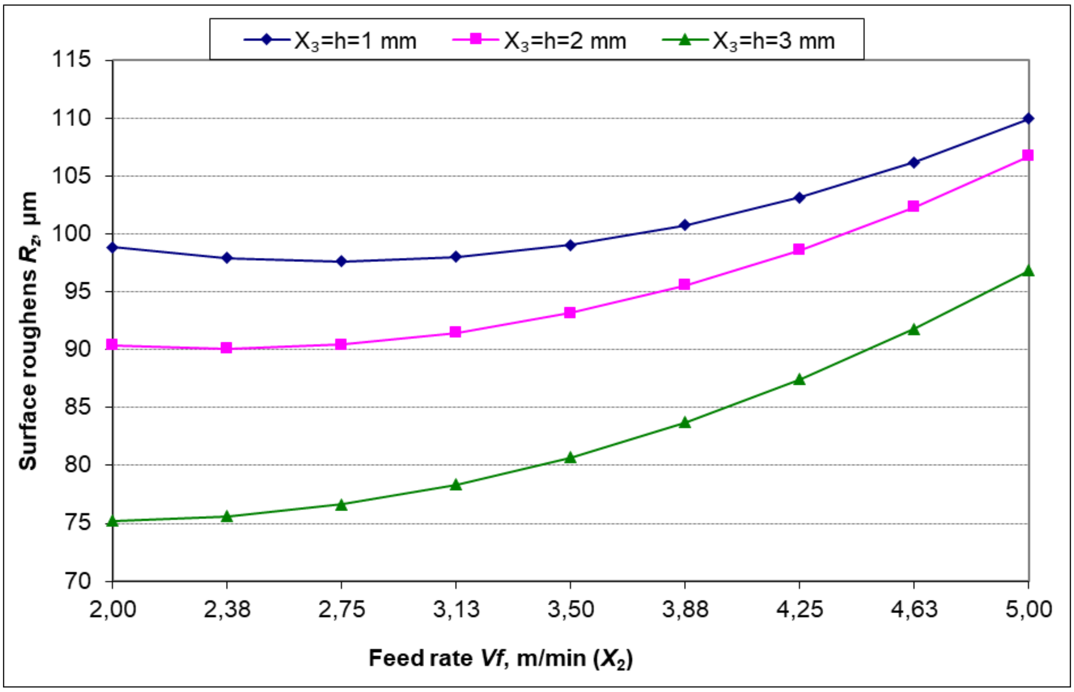

Fig. 6 Modification of the roughness parameter *Rz* depending on the feed rate (V_f) and radial depth of cut (*h*).

CONCLUSION

Based on the results of our study, the following conclusions can be drawn:

- The roughness of the processed surface is greatly influenced by the feed rate (V_f), the rotation speed of the shank cutter (*n*) and radial depth of cut (*h*);
- Depending on the specific parameters of the variable factors (V_f and *h*), the values of the parameter R_z vary from 75 µm to 110 µm. Under the conditions of this study, the most significant impact had the feed rate (V_f). Its increase resulted in an increase in the roughness parameter R_z.
- The best quality of the processed surfaces is observed in the following optimal values of variable factors: the rotation speed of the shank cutter n = 18000 min^{-1}, feed rate V_f = 3.5 m.min^{-1} and radial depth of cut h = 3 mm.

Based on the results, it could be concluded that the MDF workpieces, processed by CNC machines, should be milled at higher rotation speeds of the shank cutter ($n > 16000$ min^{-1}), at lower feed rates ($V_f < 5$ m.min^{-1}) and radial depth of cut $h > 2$ mm.

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