ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 66(2): 75−87, 2024
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2024.66.2.07

THE EFFECT OF THE FOCAL LENGTH POSITION OF THE FOCUSING LENS ON THE DISCOLORATION ROUGHNESS OF PLYWOOD UNDER DIFFERENT CO2 LASER ENGRAVING MODES

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ABSTRACT

The results of a surface roughness study obtained by CO2 laser engraving of birch plywood specimens are presented in the paper. A ZnSe lens with focal length F = 50.8 mm; focal position ΔF = -4, -6, and -8 mm above the material surface; laser beam power P = 4.0, 5.6, and 7.2 W; laser beam scanning speed vf = 250, 260, and 270 mm/s was used for the research. The roughness of the treated surfaces was measured with an electronic profilometer, model Surftest SJ-210 (Mitutoyo – Japan).

The experimental results were evaluated via the parameters Ra, Rq, and Rz and analyzed using specialized software Q-StatLab, ANOVA analysis, and interaction diagrams of all parameters, and relevant conclusions and recommendations were made.

The analyses indicate that the surfaces of birch plywood treated with a CO2 laser exhibit higher roughness than untreated ones, with a deviation of 2 to 4 times greater for the Ra parameter and 2.2 to 3.9 times greater for the Rz parameter. The primary reason for the difference in surface roughness of CO2 laser-treated materials at different focusing positions on the surface is the varying laser beam power density. A higher beam power density leads to more significant absorbed heat, resulting in increased surface roughen.

Keywords: CO2 laser engraving; birch wood; plywood; roughness of surfaces.

INTRODUCTION

Laser technologies based on different types of laser sources are widely used in the modern wood and furniture industry. One main use of CO2 lasers is cutting and engraving solid wood and wood-based materials (WBM).

Modern software products, part of laser technologies, open vast possibilities for building complex graphic images, a type of photography, on solid wood and WBM samples. This opens up new challenges for the furniture industry, not least for the souvenir industry.

Along with the development of laser technology, researchers are particularly interested in the study of the mechanism of the laser beam's interaction with different types of wood and WBM. The main guidelines being worked on are the most appropriate modes to be applied, depending on the objective set and the specific type of material.

The most commonly investigated factors of CO2 lasers are the power and feed (scan) speed of the laser beam, the focal length of the focusing optics and, the position of the focus relative to the surface of the material to be processed, the mode structure of the beam. The object of study is the formation of the slot and its parameters, the modifications that occur in the processed material, the changes in the color of the engraved surfaces as a result of carbonization of the wood material, etc. (Orech and Jůza, 1987; Gotchev *et al.,* 1994; Gochev, 1996; Gochev and Dinkov, 1996; Dinkov *et al.,* 1996; Batov *et al.,* 1997; Pagano *et al.,* 2009; Kubovský *et al.,* 2012; Hernández-Castañeda *et al.,* 2011; Eltawahni *et al.,* 2013; Petutschnigg *et al.,* 2013; Gochev, 2016; Gurau *et al.,* 2017; Martinez-Conde *et al.,* 2017; Vidholdová *et al.*, 2017; Sikora *et al.*, 2018; Jurek and Wagnerová, 2021; Gochev and Vichev, 2022; Kúdela *et al.,* 2022; Gochev, 2023 and others.).

Information can be found in the literature from different authors about the changes that occur in the color of various types of solid wood and WBM when engraving or decorating with a CO2 laser beam (Petutschnigg *et al.,* 2013; Gurau *et al.,* 2017; Vidholdová *et al.,* 2017; Sikora *et al.,* 2018; Jurek and Wagnerová, 2021; Gochev and Vichev, 2022; Kúdela *et al.,* 2022; Jurek and Wagnerová, 2021 and others). When building complex graphic images, the different color shades stand out best when engraving with a laser beam on homogeneous solid wood and WBM. Several authors have also investigated the influence that the roughness of the carbonized material has on the quality of graphic images (Gurau *et al.,* 2017; Kúdela *et al.,* 2022; Li *et al.,* 2022; Kúdela *et al.,* 2023; and others).

The aim of the present work is to investigate the surface roughness obtained during CO2 laser engraving of birch plywood samples and the influence of the different positions of the focusing lens over the material surface at various powers and scanning speeds of the CO2 laser beam, as well as to formulate relevant conclusions and recommendations.

MATERIALS AND METHODS

The experimental studies were conducted using a FormaTec laser engraving and cutting machine, model K40 with 40 W power (Fig. 1).

Fig. 1 CO2 laser engraving and cutting machine.

For the experiment, plywood samples were used – common birch (*Betula pendula Roth.)* with dimensions 200 × 200 × 3 mm, density ρ = 400 kg/m^3 and humidity W = 6%. Birch plywood is manufactured from developed birch veneer and is characterized by high strength and dimensional stability. Birch is a hard broad-leaved tree species with a light, smooth, even surface and a homogeneous, fine structure, making it suitable for CO2 laser engraving.

A test was performed on plywood samples to examine the color change in the surface layer when varying the laser beam power (P, W); scan speed (v_f, mm/s) and focal length of a ZnSe lens, F = 50.8 mm. For each matrix series of the planned experiment, the focal position was above the material surface: ΔF = - 4 mm; ΔF = - 6 mm and ΔF = - 8 mm (Fig. 2).

The values of the variable factors – laser beam power (P, W) and laser beam scan (feed) speed (v_f, mm/s) in open and coded form are given in Table 1.

A high-precision roughness profilometer, model Surftest SJ-210 (Mitutoyo - Japan), was used to measure the roughness changes in the surface layer color of the birch plywood samples (Fig. 3). When the position of the focus (ΔF) is above the surface of the material, it is taken as "minus", when it is on the surface as "0" and when it is below the surface of the material as "plus".

The matrix of the planned two-factor experiment is shown in Table 2.

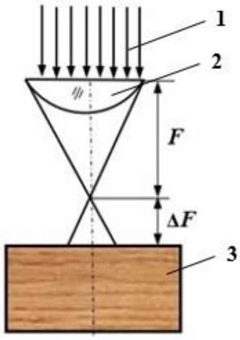


Fig. 2 Position of the focal plane of the focusing lens above the surface of the material: 1 – laser beam; 2 – focusing lens; 3 – processed material.

Tab. 1 Variable factor values.

Variable factors	Minimum value		Average value		Maximum value	
	open form	coded form	open form	coded form	open form	coded form
$X_1 = P$, W	4.0	-1	5.6	0	7.2	+1
$X_2 = v_f$, mm/s	250	-1	260	0	270	+1

Tab. 2 Matrix of the planned two-factor experiment.

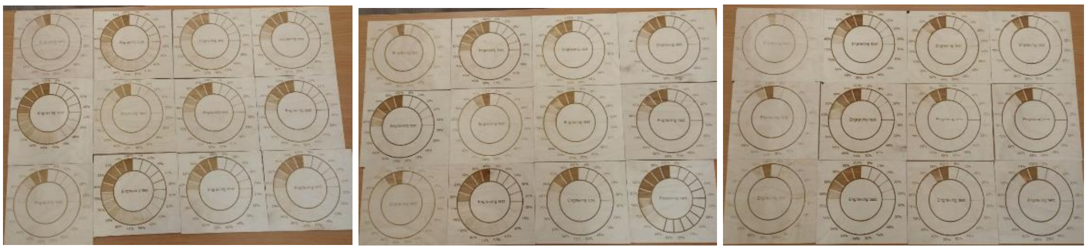
№ of the experiment	Variable factors			
	$X_1 = P$, W		$X_2 = v_f$, mm/s	
1.	-1	4.0	-1	250
2.	+1	7.2	-1	250
3.	-1	4.0	+1	270
4.	+1	7.2	+1	270
5.	-1	4.0	0	260
6.	+1	7.2	0	260
7.	0	5.6	-1	250
8.	0	5.6	+1	270
9.	0	5.6	0	260
Experiments in the middle of the factor space				
10.	0	5.6	0	260
11.	0	5.6	0	260
12.	0	5.6	0	260

RESULTS AND DISCUSSION

The results of the test conducted on the color change of the surface layer of the plywood samples, according to the matrix of the planned two-factor experiment, are shown in Figure 4, for different focus positions ΔF above the material surface. The arrangement of the samples was made vertically, in four rows, according to the experiment matrix of Table 2.

On the surface of the samples shown in Fig. 4 is an engraved system of isolated areas with different color from dark brown to light, approaching the natural color of birch plywood. Specialized software was used to conduct this test „*Inkscape*" (https://wikibgbg.top/wiki/Inkscape; https://paradacreativa.es/bg/que-es-inkscape-y-como-funciona/). For each experience of the planned experiment matrix (Table 2), the laser beam power was varied from 100% to 5% with a step of 5%.

Fig. 3 Roughness profilometer, model Surftest SJ-210, Mitutoyo – Japan.



A B C

Fig. 4 Test for colour change in the surface layer of birch plywood at: A – ∆*F* = - 4 mm; B – ∆*F* = - 6 mm; C – ∆*F* = - 8 mm.

Since the volume of roughness measurements, for each effect zone, is very large, as can be seen in Figures 3 and 4, only the results of the areas affected with the laser beam at 100% power are presented here, according to the experiment matrix in Table 2.

The values of *R*a (*the absolute mean difference between the peak and valley of the irregularities, within the reference length l*), *R*q (*the root mean square deviation of the evaluated profile from the mean line within the reference length l*) and *R*z (*the absolute arithmetic mean sum of the five largest peaks and the five largest valleys, within the reference length l*) were used to evaluate the roughness of the surface irradiated by the laser beam (BDS EN ISO 4287:2006). Each measurement was carried out in the area of influence, repeating the measurements three times in different directions to obtain averaged values (Table 3, 4 and 5).

Tab. 3 Surface roughness parameters at ΔF = -4 mm.

№ of the experiment	Variable factors		Output factors		
	$X_1 = P$, W	$X_2 = v_f$, mm/s	Y = *R*a, µm	Y = *R*q, µm	Y = *R*z, µm
1.	4.0	250	9.47	12.12	59.01
2.	7.2	250	24.59	29.65	119.98
3.	4.0	270	14.42	17.29	83.09
4.	7.2	270	21.59	26.05	106.29
5.	4.0	260	13.72	17.74	84.66
6.	7.2	260	21.33	26.03	106.83
7.	5.6	250	19.06	23,59	98.84
8.	5.6	270	17.32	21,45	94.48
9.	5.6	260	20.66	25.59	111.19
Experiments in the middle of the factor space					
10.	5.6	260	24.69	30.34	128.69
11.	5.6	260	19.03	23.36	98.71
12.	5.6	260	16.88	21.32	94.68

Tab. 4 Surface roughness parameters at ΔF = -6 mm.

№ of the experiment	Variable factors		Output factors		
	$X_1 = P$, W	$X_2 = v_f$, mm/s	Y = *R*a, µm	Y = *R*q, µm	Y = *R*z, µm
1.	4.0	250	7.00	9,27	49.31
2.	7.2	250	19.44	23.91	97.84
3.	4.0	270	10.37	13.67	69.51
4.	7.2	270	18.03	22.19	94.67
5.	4.0	260	7.80	10.42	55.64
6.	7.2	260	13.04	16.39	73.99
7.	5.6	250	16.46	20.60	91.07
8.	5.6	270	17.42	21.55	93.48
9.	5.6	260	20.32	24.69	105.85
Experiments in the middle of the factor space					
10.	5.6	260	16.49	20.48	90.09
11.	5.6	260	15.92	19.61	83.20
12.	5.6	260	19.05	23.26	98.06

Tab. 5 Surface roughness parameters at ΔF = -8 mm.

№ of the experiment	Variable factors		Output factors		
	$X_1 = P$, W	$X_2 = v_f$, mm/s	Y = *R*a, µm	Y = *R*q, µm	Y = *R*z, µm
1.	4.0	250	5.62	7.33	38.32
2.	7.2	250	11.15	20.68	89.85
3.	4.0	270	5.42	7.35	27.30
4.	7.2	270	17.49	21.71	67.55
5.	4.0	260	8,84	11.51	54.94
6.	7.2	260	16.96	20.48	85.00
7.	5.6	250	11.22	19.86	88.58
8.	5.6	270	14.12	17.42	76.31
9.	5.6	260	14.55	18.60	86.52
Experiments in the middle of the factor space					
10.	5.6	260	13.06	16.95	78.12
11.	5.6	260	13.16	16.73	76.20
12.	5.6	260	17.51	21.71	90.62

In North America the most commonly used surface roughness parameter is *R*a, while in Europe, the more common roughness parameter is *R*z.

The *R*a parameter is statistically stable and repeatable, but it does not distinguish between peaks and valleys of the profile.

The *R*z parameter averages only the five highest peaks and the five deepest valleys - therefore the extreme values have a much greater influence on the final result.

The *R*q parameter is more sensitive to peaks and valleys than *R*a and is commonly used in in research and statistical control of very smooth surfaces (Kalimanova *et al.*, 2012).

Which parameter to use to evaluate the surface roughness *R*z or *R*a depends on the manufacturer and the customer. It is recommended as a safe conversion to use a ratio range for *R*z to *R*a = 4:1 to 7:1 (https://www.productionmachining.com/articles/the-difference-between-ra-and-rz, Kovács *et al.*, 2012), but this is still an example of not good engineering practice.

Because using *R*a alone may cause some points, such as single convexities, to be neglected, it is better to use *R*a and *R*z together. In this study, results are also given for the parameter *R*q to obtain a more complete picture.

Figure 5 shows a roughness profile from the surface of a birch plywood sample not treated with a CO2 laser beam, and Figures 6, 7 and 8 after laser beam treatment at the position of the focus above the material surface (ΔF = -4 mm, ΔF = -6 mm and ΔF = -8 mm). The roughness profiles in Figs. 6, 7, and 8 were obtained for variable factor parameters corresponding to No. 10 in Table 2.

To compare the individual profiles in Figures 5, 6, 7 and 8, they are overlaid in a single Figure 9.

It can be seen from all the above figures that:

- the CO2 laser-treated surfaces of the birch plywood samples have a greater roughness than the untreated ones, and for the parameter *R*a, the variation is from 2 to 4 times, and for *R*z from 2.2 to 3.9 times;
- the largest roughness of the CO2 laser treated surfaces is obtained at the focal position ΔF = -4 mm above the material surface and the smallest at ΔF = -8 mm, an intermediate position for the surface roughness is obtained at ΔF = -6 mm;
- the ratio of ΔF = -4 mm to ΔF = -6 mm and to ΔF = -8 mm for *R*a is 2.0:1.7:1.2 and for *R*z is 1.8:1.5:1.2;
- the main reason for the different roughness of the CO2 laser treated surfaces at different focus positions over the material surface is the different power density of the laser beam (Fig. 2);
- at all three focus positions, an unfocused laser beam falls on the plywood samples, but at ΔF = -4 mm the spot diameter is the smallest and the power density is the largest, while at ΔF = -8 mm the spot diameter is the largest and the power density is the smallest;
- greater beam power density leads to a greater amount of absorbed heat and increased surface roughness.

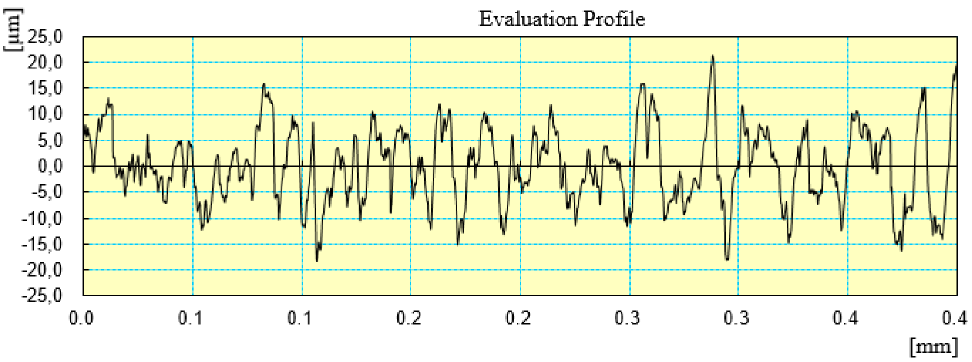


Fig. 5 Surface roughness profile of a birch plywood sample not exposed to a CO2 laser beam (*R*a = 5.84 μm, *R*q = 7.11 μm, *R*z = 32.58 μm).

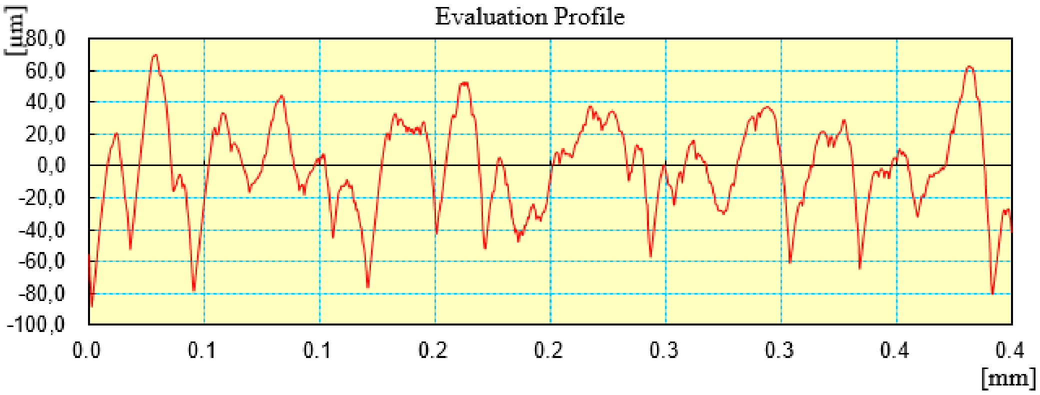


Fig. 6 Surface roughness profile of a birch plywood sample exposed to a CO_2 laser beam at ΔF = -4 mm (*R*a = 23.18 µm, *R*q = 28.72 µm, *R*z = 125.29 µm).

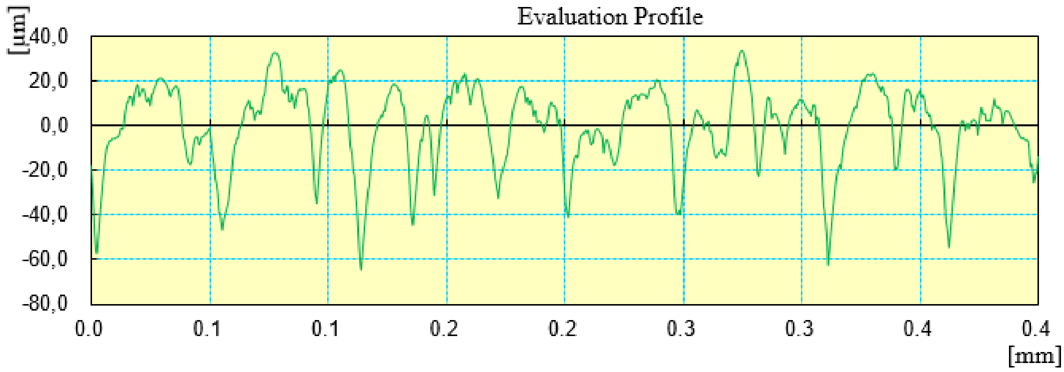


Fig. 7 Surface roughness profile of a birch plywood sample exposed to a CO_2 laser beam at ΔF = -6 mm (*R*a = 13.96 µm, *R*q = 17.75 µm, *R*z = 82.88 µm).

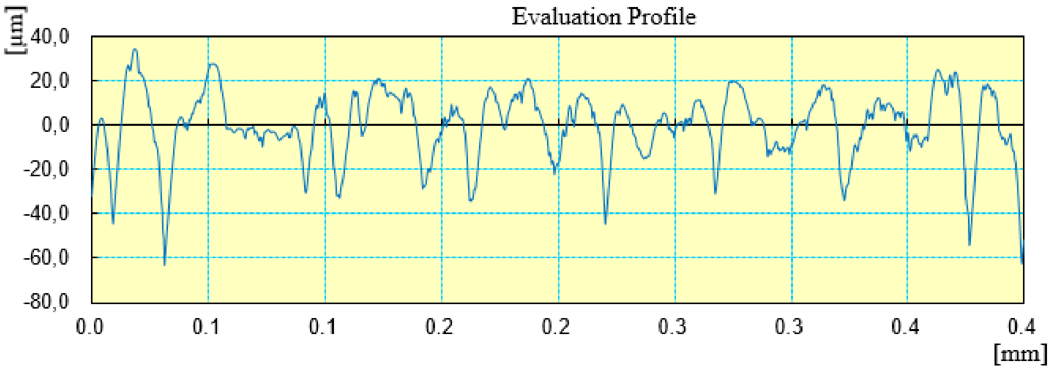


Fig. 8 Surface roughness profile of a birch plywood sample exposed to a CO_2 laser beam at ΔF = -8 mm (*R*a = 11.73 µm, *R*q = 15.14 µm, *R*z = 70.78 µm).

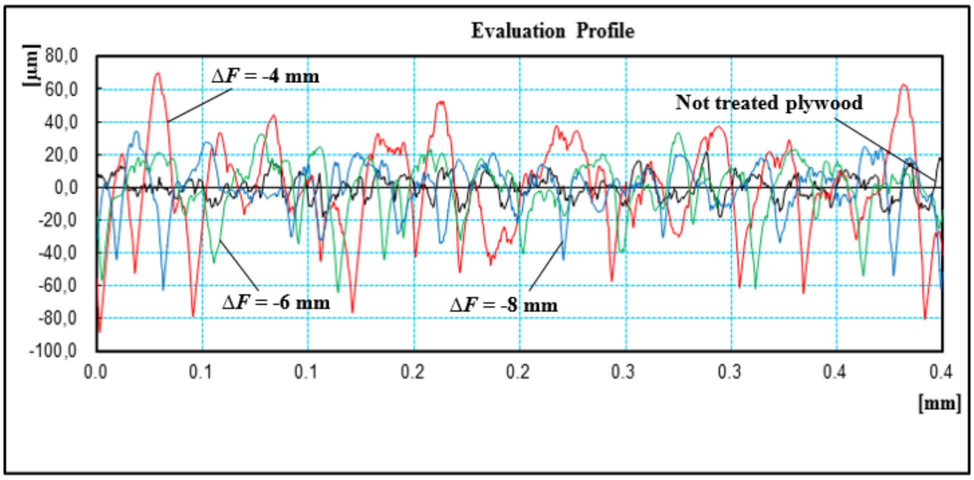


Fig. 9 Various machined surface roughness profiles.

The results of the experimental studies were processed mathematically with specialized Q-StatLab software and regression equations were derived for the roughness parameters *R*a and *R*z at different focal positions on the material surface:

- Regression equation for *R*a at ΔF = -4 mm

$$Y_1 = 19.98 + 4.98X_1 - 0.035X_2 + 1.74X_1^2 - 1.078X_2^2 - 1.98X_1X_2 \quad (1)$$

- Regression equation for *R*a at ΔF = -6 mm

$$Y_1 = 17.22 + 4.22X_1 - 0.49X_2 + 5.38X_1^2 - 1.14X_2^2 - 1.19X_1X_2 \quad (2)$$

- Regression equation for *R*a at ΔF = -8 mm

$$Y_1 = 14.75 + 4.29X_1 - 1.51X_2 + 2.21X_1^2 - 2.44X_2^2 - 1.63X_1X_2 \quad (3)$$

- Regression equation for *R*z at ΔF = -4 mm

$$Y_2 = 106.98 + 17.72X_1 - 1.005X_2 + 8.57X_1^2 - 7.655X_2^2 - 9.44X_1X_2 \quad (4)$$

- Regression equation for *R*z at ΔF = -6 mm

$$Y_2 = 91.79 + 15.34X_1 - 3.24X_2 + 21.96X_1^2 - 5.496X_2^2 - 5.842X_1X_2 \quad (5)$$

- Regression equation for *R*z at ΔF = -8 mm

$$Y_2 = 85.164 + 20.306X_1 - 7.598X_2 + 19.792X_1^2 - 7.317X_2^2 - 0.61X_1X_2 \quad (6)$$

The equations show that it is the coefficient in front of X_1 corresponding to the cutting power (*P*) that will have the greatest influence, and to a greater extent than feed rate (v_f), on the roughness of the surfaces.

The sign in front of the coefficient is “plus”, i.e., as *P* increases, *R*a and *R*z will increase. The coefficient in front of X_2 has a negative sign, i.e., with increasing feed rate (scanning) *R*a and *R*z will decrease. The sign in front of the coefficient of double interactions X_{12} is negative, indicating the divergent influence of laser beam power (*P*) and feed rate (v_f) on the surface roughness.

Figures 10 – 15 present the graphical relationships showing the variation of the roughness parameters *R*a and *R*z with laser beam power (P) at different feed rates (*vf*) and at focal distance ΔF = -4 mm; ΔF = -6 mm and ΔF = -8 mm.

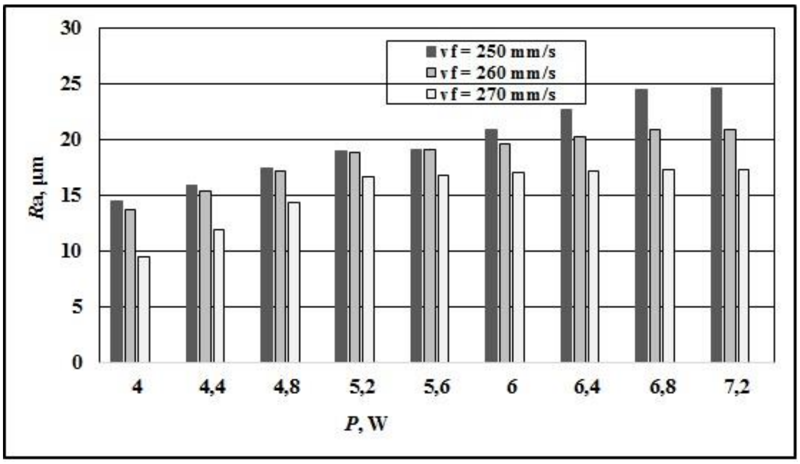


Fig. 10 Variation of the roughness parameter *R*a with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>ΔF = -4 mm.</u>

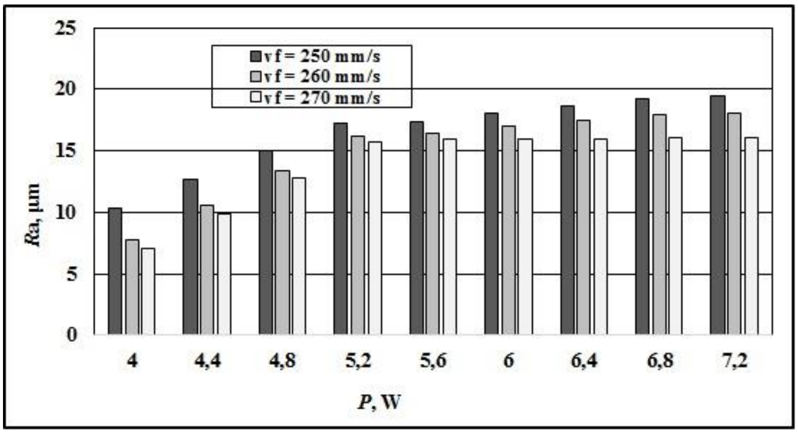


Fig. 11 Variation of the roughness parameter *R*a with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>ΔF = -6 mm</u>.

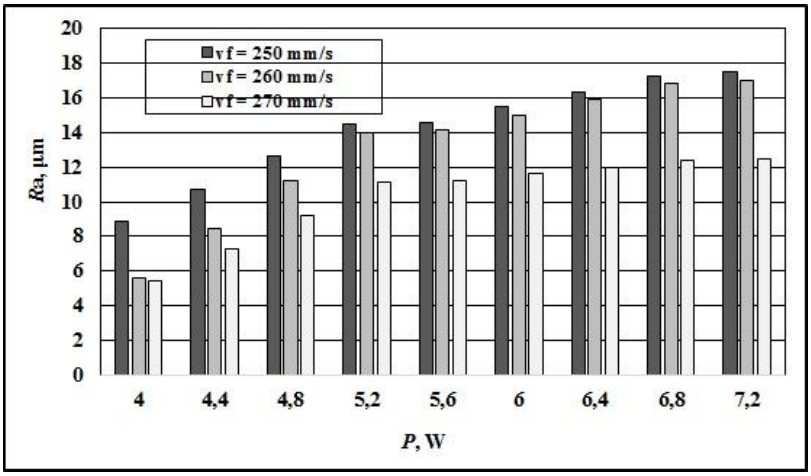


Fig. 12 Variation of the roughness parameter *R*a with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>ΔF = -8 mm.</u>

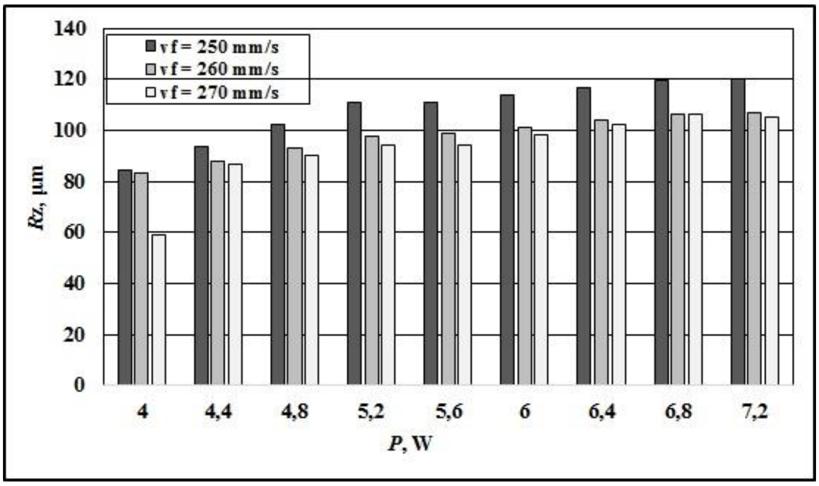


Fig. 13 Variation of the roughness parameter *R*z with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>ΔF = -4 mm.</u>

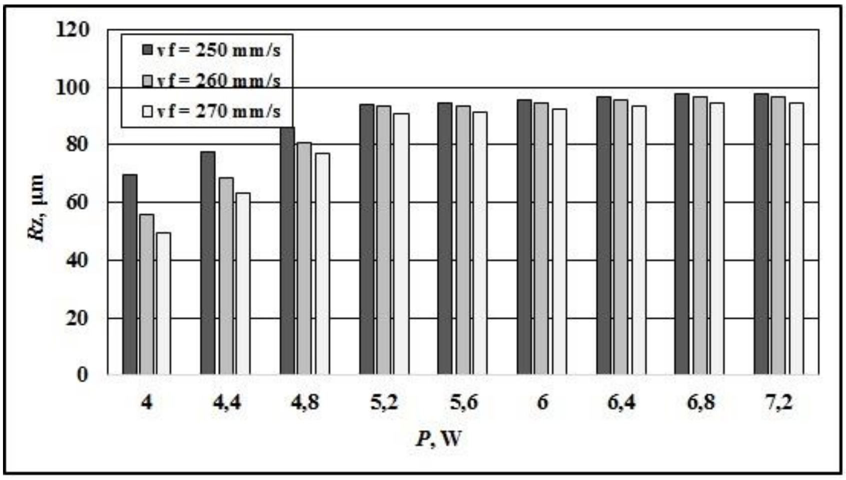


Fig. 14 Variation of the roughness parameter *R*z with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>Δ*F* = -6 mm.</u>

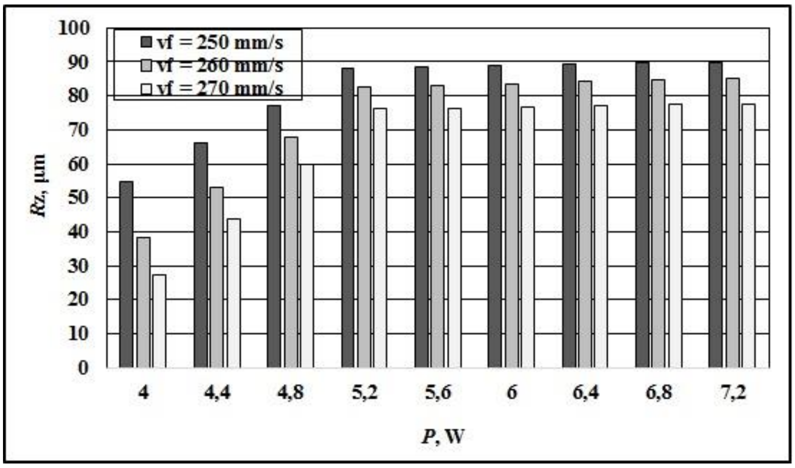


Fig. 15 Variation of the roughness parameter *R*z with laser beam power (*P*) at different feed rates (*v*f) and focal length <u>Δ*F* = -8 mm.</u>

CONCLUSION

Based on the conducted research, the following conclusions can be drawn:

- The surfaces of birch plywood samples treated with a CO2 laser exhibit higher roughness than untreated ones, with 2 to 4 times more significant deviations for the Ra parameter and 2.2 to 3.9 times more significant for the Rz parameter.
- The highest values of surface roughness parameters for CO2 laser-treated surfaces are obtained at the focal position ΔF = -4 mm above the material surface, (laser beam power P = 7.2 W and feed rate vf = 250 mm/s) and the smallest at ΔF = -8 mm laser beam power P = 4 W and feed rate vf = 270 mm/s), an intermediate position for the surface roughness is obtained at ΔF = -6 mm.
- At the focusing position above the material surface ΔF = -4 mm, the material loss is greater than at the ΔF = -6 mm and ΔF = -8 mm positions. In the first case, the diameter of the unfocused laser beam is smaller, the power density is higher, and the amount of evaporated material is greater than at ΔF = -6 mm and ΔF = -8 mm, which is reflected in higher values of Ra, Rz, and Rq (Figures 5-15).
- As the laser beam power increases (P – from 4 to 7.2 W), the values of Ra and Rz increase, and the surface roughness of the processed areas also increases (Figures 10-15).
- Increasing the feed rate (scanning – vf from 250 to 270 mm/s) of the laser beam, the values of the roughness parameters Ra and Rz decrease, as the time of the laser beam impact on the material decreases, leading to a decrease in the degree of carbonization of the surface layer, and hence to a decrease in its roughness.
- The ratio of ΔF = -4 mm to ΔF = -6 mm and ΔF = -8 mm for Ra is 2.0:1.7:1.2, and for Rz, it is 1.8:1.5:1.2 (Table 3-5 and Figure 9).
- Depending on the effect achieved when creating complex graphic patterns using the laser beam, modes can be developed in which a specific shade between the darkening of the material's surface layer and its roughness is achieved. This will be the subject of further research.

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ACKNOWLEDGMENT

We would like to thank the Research Sector of the University of Forestry, Sofia, Bulgaria, with whose support, through Contract No. NIS-B-1284/19.10.2023, this research was carried out.

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