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Influence of Focal Length Position of Focusing Lens on Plywood Discoloration Under Different Modes of CO_2 Laser Engraving

Utjecaj položaja žarišne duljine fokusne leće na promjenu boje furnirske ploče pri različitim parametrima graviranja CO_2 laserom

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ABSTRACT • *This paper presents the results of a study of the laser engraving process on birch plywood samples. The influence of the focal distance of the focusing lens at different positions relative to the surface of the material on the discoloration of plywood samples, at different power and scanning speed of a CO_2 laser beam, was investigated. The change in the color shades of the plywood was studied with an LS173 calorimeter. For this research, the following parameters were used: ZnSe lens with focal length F = 50.8 mm; the position of the focal plane of the focusing lens relative to the surface of the material ΔF = 4, 6, and 8 mm; laser beam power P = 4.0; 5.6 and 7.2 W; feed rate of the laser beam V_f = 250; 260 and 270 mm/s. The color shade difference of the plywood samples was measured in the L*, a* and b* color space. The results allow to define modes for surface treatment with laser beam in the construction of complex graphic images on plywood products.*

KEYWORDS: *CO_2 laser beam; focal distance; calorimeter; discoloration; colour space; birch plywood; surface treatment*

SAŽETAK • *U ovom su radu predstavljeni rezultati istraživanja laserskog graviranja na uzorcima furnirske ploče od brezovine. Istražen je utjecaj položaja žarišne duljine fokusne leće u odnosu prema površini materijala na promjenu boje uzoraka furnirske ploče uz primjenu CO_2 laserske zrake različite snage i brzine. Promjene nijansi boje furnirske ploče proučavane su kolorimetrom LS173. U ovom je istraživanju primijenjena ZnSe leća žarišne duljine F = 50,8 mm; položaj žarišne ravnine fokusne leće s obzirom na površinu materijala bio je ΔF = 4; 6 i 8 mm; snaga laserske zrake P = 4,0; 5,6 i 7,2 W, a posmična brzina laserske zrake V_f = 250; 260 i 270 mm/s. Razlika u nijansama boje uzoraka furnirske ploče mjerena je u L*, a* i b* prostoru boja. Rezultati omogućuju pregled načina obrade površine laserskom zrakom pri izradi složenih grafičkih slika na proizvodima od furnirske ploče.*

KLJUČNE RIJEČI: *CO_2 laserska zraka; žarišna duljina; kolorimetar; promjena boje; prostor boja; furnirska ploča od brezovine; površinska obrada*

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1 INTRODUCTION
1. UVOD

Laser engraving is one of the most up-to-date and effective methods for engraving wood and wood-based materials (WBM). Today, this technology can also be used at home thanks to the development of affordable and compact laser engravers. Different laser engravers are used for engraving wood and WBM based on diode lasers, CO_2 lasers and fiber lasers.

CO_2 lasers use a gas mixture to generate the laser beam; they are versatile, operate at higher speeds and power, and are widely used for cutting and engraving wood and WBM.

In laser engraving, the material is heated very strongly by the laser beam and the surface layer is vaporized or burned. The sharpness and the contrast of the engraving, as well as the resulting shade after the process is completed, depend on various factors, including adjustment of the focus distance, the power and speed of the laser beam, all depending on the type and thickness of the wood or WBM.

In a number of literature sources, the changes in the color of wood, as a result of the impact of CO_2 laser radiation, and the possibilities for engraving or decorating at different power and speeds of the laser beam, have been investigated (Pagano *et al.,* 2009; Leone *et al.,* 2009; Hernández-Castañeda *et al.,* 2011; Eltawahni *et al.,* 2013; Petutschnigg *et al.,* 2013; Kubovský and Kačík, 2013; Kubovský and Igaz, 2014; Kúdela *et al.,* 2018; Kubovský and Kačík, 2014; Yakimovich *et al.,* 2016; Gurau *et al.,* 2017; Martinez-Conde *et al.,* 2017; Vidholdová *et al.,* 2017; Sikora *et al.,* 2018; Jurek *et al.,* 2021; Kúdela *et al.,* 2022; Kúdela *et al.,* 2023; Chernykh *et al.,* 2024 and others). The influence of laser radiation with a CO_2 laser on the discoloration of different types of wood was analyzed: beech, oak, spruce, pine, birch, aspen, larch, lime, afromosia wood, beech veneer and others. The degree of discoloration of the wood surface depends on the amount and type of energy supplied and the absorption characteristics of the main wood components. The most frequently studied parameters were laser power, beam speed, laser beam emission mode (CW or pulse), and the number of laser scans. It was established through chemical analysis of the surface of spruce wood that discoloration is mainly due to heat-induced cleavage of C=O groups in the lignin and hemicellulose structures (Kúdela *et al.,* 2023).

Laser engraving of complex photographic images on the wood surface is a difficult task, and to optimize the result and quality of the output, it is necessary to control every aspect of the laser engraving process (Jurek *et al.,* 2021).

Most of the studies in the literature were conducted when the focus position of the laser beam focus point was located exactly on the surface of the engraving material (Figure 1A). In this case, the spot size of the focused laser beam is minimal, and the power density of the beam is maximal.

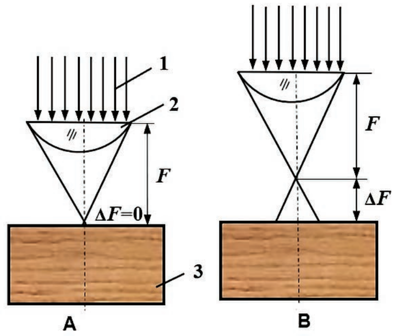

Figure 1 Position of focal plane of focusing lens on the surface (A) and above the surface (B) of the material: 1 – laser beam; 2 – focusing lens; 3 – processed material
Slika 1. Položaj žarišne ravnine fokusne leće na površini (A) i iznad površine (B) materijala: 1 – laserska zraka; 2 – fokusna leća; 3 – obrađivani materijal

The focus of the focusing lens and the position of the focal plane in relation to the workpiece surface are very important to the engraving process.

The focus position of the laser beam above the workpiece surface is considered negative ($-\Delta F$), on the surface zero ($\Delta F = 0$) and below the surface positive ($+\Delta F$).

The aim of the present work is to study the influence of CO_2 laser beam parameters, power and scanning speed at different focus positions above the surface of birch plywood samples and discoloration when engraving complex graphic images. The study is a continuation of the results obtained by the authors at the positions of the focus on the surface of the material with the same parameters of the laser beam (Gochev and Vichev, 2022; Gochev and Vichev, 2024).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The experimental studies were carried out using a laser engraving and cutting machine of FormaTec, model K40 (China) with a power of 40 W (Figure 2).

Discoloration of the surface layer of the material was studied by varying the power of the laser beam (P, W) and scan speed (V_f, mm/s), wiht focal length of ZnSe lens, F = 50.8 mm. The focus position for each series of the matrix of the planned experiment was above the surface of the material: ΔF = - 4 mm; ΔF = - 6 mm and ΔF = - 8 mm.

Plywood samples – common birch (*Betula pendula* Roth.) with dimensions 200 mm × 200 mm × 3 mm, density ρ = 400 kg/m^3 and humidity W = 6 % were used as the research material.

Figure 2 CO_2 laser machine for engraving and cutting
Slika 2. CO_2 laser za graviranje i rezanje

The dispersion analysis methodology was used to evaluate the results of the two-factor experiment (Vuchkov *et al.,* 1986). The regression equation for two variation factors is of the form

$$y_{\mathrm{pr.v.}} = b_o + b_1 x_1 + b_2 x_2 + b_{11} x_1^2 + b_{22} x_2^2 + b_{12} x_1 x_2 \quad (1)$$

Where:
$y_{\mathrm{pr.v}}$ – predicted value of output quantity,
b_o – coefficient before free member,
b_1 and b_2 – coefficients before linear member,
b_{11} and b_{22} – coefficients before non-linear equation members.

The values of the variable factors – power of the laser beam (P, W) and speed of scanning (feed rate) of the laser beam (V_f, mm/s) in explicit and coded form are given in Table 1. The matrix of the planned two-factor experiment is shown in Table 2.

To measure the difference in colors of a standard sample (without laser exposure) and on the examined sample (after exposure to a laser beam) a portable colorimeter for color difference, model LS173 (China), was used, as shown in Figure 3. The device allows measurements in two color spaces $L^*a^*b^*$ and $L^*c^*h^*$.

Table 1 Variable factor values
Tablica 1. Vrijednosti varijabilnih faktora

Variable factors *Varijabilni faktori*	**Minimum value** *Najmanja vrijednost*		**Average value** *Srednja vrijednost*		**Maximum value** *Najveća vrijednost*	
	Explicit value *Stvarna vrijednost*	Coded value *Kodirana vrijednost*	Explicit value *Stvarna vrijednost*	Coded value *Kodirana vrijednost*	Explicit value *Stvarna vrijednost*	Coded value *Kodirana vrijednost*
$X_1 = P$, W	4.0	-1	5.6	0	7.2	+1
$X_2 = V_f$, mm/s	250	-1	260	0	270	+1

Table 2 Matrix of planned two-factor experiment
Tablica 2. Matrica planiranoga dvofaktorskog eksperimenta

№ of experiment *Broj eksperimenta*	**Variable factors** / *Varijabilni faktori*			
	$X_1 = P$, **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 *Eksperimenti u sredini faktorskog prostora*				
10	0	5.6	0	260
11	0	5.6	0	260
12	0	5.6	0	260

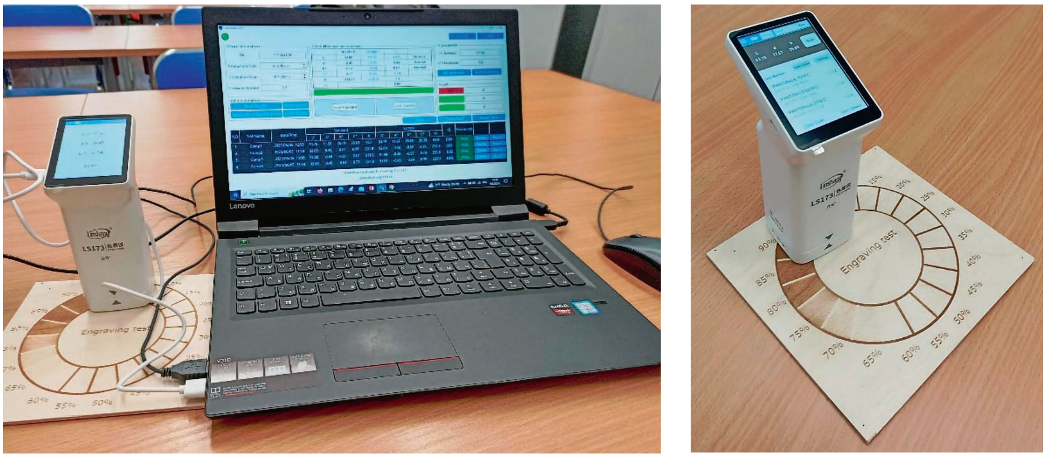

Figure 3 Colorimeter, model LS173
Slika 3. Kolorimetar, model LS173

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The results of the studies on the changes in the discoloration of the plywood samples, according to the matrix of the planned two-factor experiment, are shown in Figures 4, 5 and 6 for different positions of the focus ΔF above the surface of the material. The arrangement of the samples was made vertically, in four rows, according to the experiment matrix of Table 2.

The difference in discoloration shades of the plywood samples is measured in a three-dimensional color model, with CIELAB (L^* a^* b^*) being used as a reference standard.

A system of isolated zones with different colors, from dark brown to light, approaching the natural color of birch plywood, was engraved on the surface of the samples. Specialized software *Inkscape* was used to conduct this research (https://wikibgbg.top/wiki/Inkscape; https://paradacreativa.es/bg/que-es-inkscape-y-como-funciona/). For each experiment from the planned matrix (Table 2), the power of the laser beam was changed from 100 % to 5 % in steps of 5 %.

To estimate the difference between two colors, the total color difference ΔE^* was used, estimated according to BDS EN ISO 11664-6:2016 and calculated by the formula

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (2)$$

Figure 5 Results of an engraving test and changes in discoloration of birch plywood at ΔF = - 6 mm
Slika 5. Rezultati testa graviranja i promjene boje furnirske ploče od brezovine pri ΔF = - 6 mm

Figure 4 Results of an engraving test and changes in discoloration of birch plywood at ΔF = - 4 mm
Slika 4. Rezultati testa graviranja i promjene boje furnirske ploče od brezovine pri ΔF = - 4 mm

Figure 6 Results of an engraving test and changes in discoloration of birch plywood at ΔF = - 8 mm
Slika 6. Rezultati testa graviranja i promjene boje furnirske ploče od brezovine pri ΔF = - 8 mm

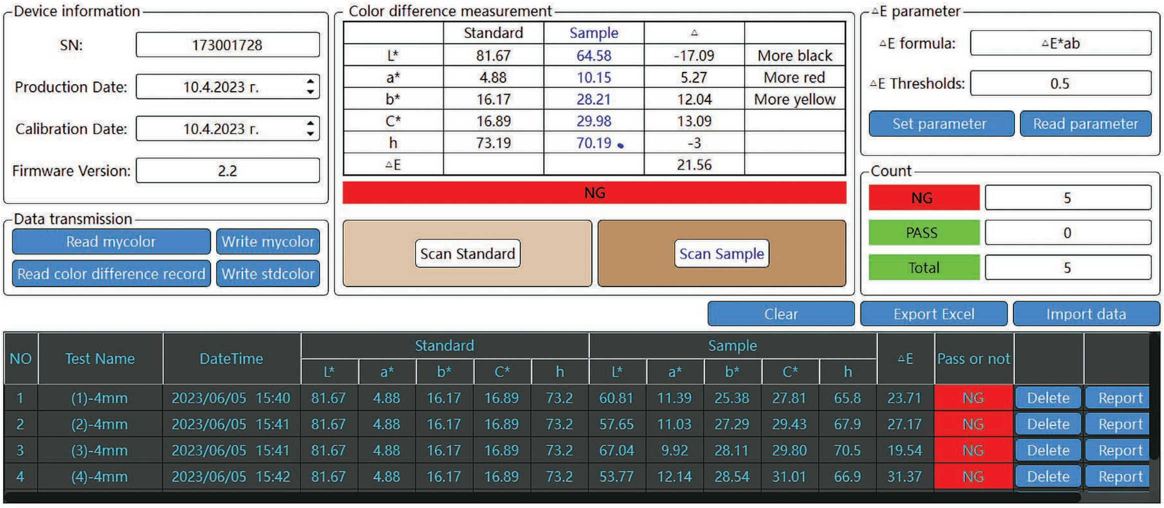

Figure 7 Results after measurement with colorimeter LS173 at ΔF = - 4 mm
Slika 7. Rezultati nakon mjerenja kolorimetrom LS173 pri ΔF = - 4 mm

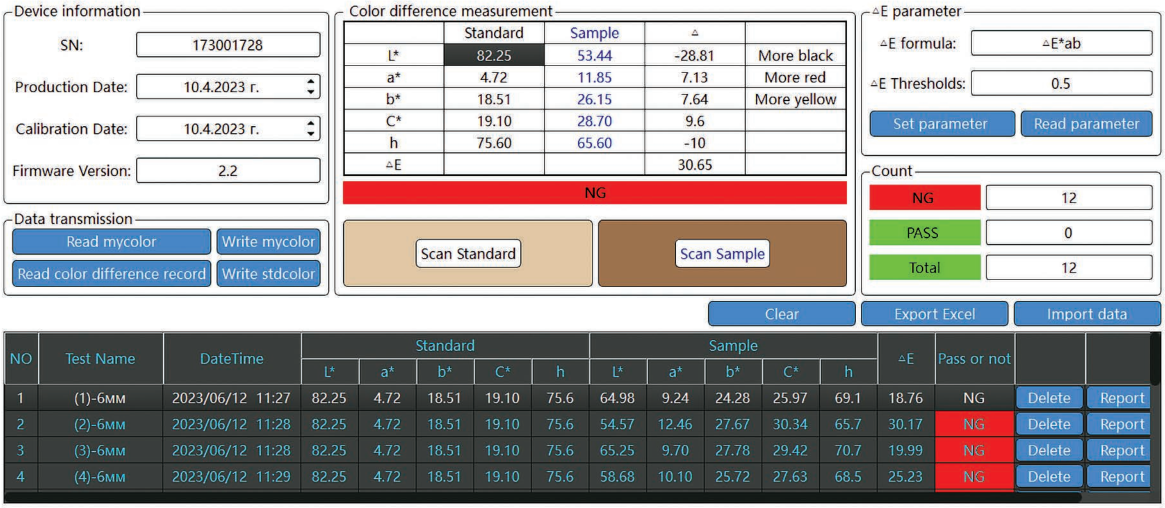

Figure 8 Results after measurement with colorimeter LS173 at ΔF = - 6 mm
Slika 8. Rezultati nakon mjerenja kolorimetrom LS173 pri ΔF = - 6 mm

Where ΔL^*, Δa^* and Δb^* are differences in individual axes (difference between values measured after laser exposure and reference sample).

The results of the measurements made using an LS173 colorimeter (Figure 3) of the changes in discoloration shades of the samples from Figures 4, 5 and 6 are represented in Figures 7, 8 and 9. Since the volume of measurements for each impact zone is very large, as seen in Figures 4, 5, and 6, only the results of the zones impacted with a 100 % power laser beam are presented here, according to the experiment matrix in Table 2.

Based on the experimental studies carried out and after mathematical processing of the data, regression equations (3); (4), and (5) were derived for ΔF = - 4 mm; ΔF = - 6 mm, and ΔF = - 8 mm using the specialized software Q-StatLab.

- Regression equation at ΔF = - 4 mm:
  $$Y_1 = 23.829 + 3.683X_1 + 0.540X_2 + 2.179X_1^2 - 1.081X_2^2 + 2.092X_1X_2 \quad (3)$$
- Regression equation at ΔF = - 6 mm:
  $$Y_1 = 29.772 + 4.420X_1 - 0.322X_2 + 0.829X_1^2 - 6.136X_2^2 - 1.542X_1X_2 \quad (4)$$
- Regression equation at ΔF = - 8 mm:
  $$Y_1 = 35.067 + 8.343X_1 + 3.828X_2 - 1.630X_1X_1 - 3.085X_2X_2 - 4.692X_1X_2 \quad (5)$$

Where:

Y_1 – expected variation of ΔE^* indicator in coded form at corresponding focal length,

X_1 – laser beam power (P) in coded form,

X_2 – scan speed (V_f) in encoded form.

From the values of the regression coefficients of equations (3), (4) and (5), it is evident that, of the two factors investigated, the laser beam power (P) has a greater influence on the discoloration of the samples. Kubovský *et al.* (2014), Kubovský *et al.* (2021), Vidholdová *et al.* (2017) and others reached a similar conclusion for the irradiation dose (H, J/cm^2), but it depends proportionally on the laser beam power (P, W).

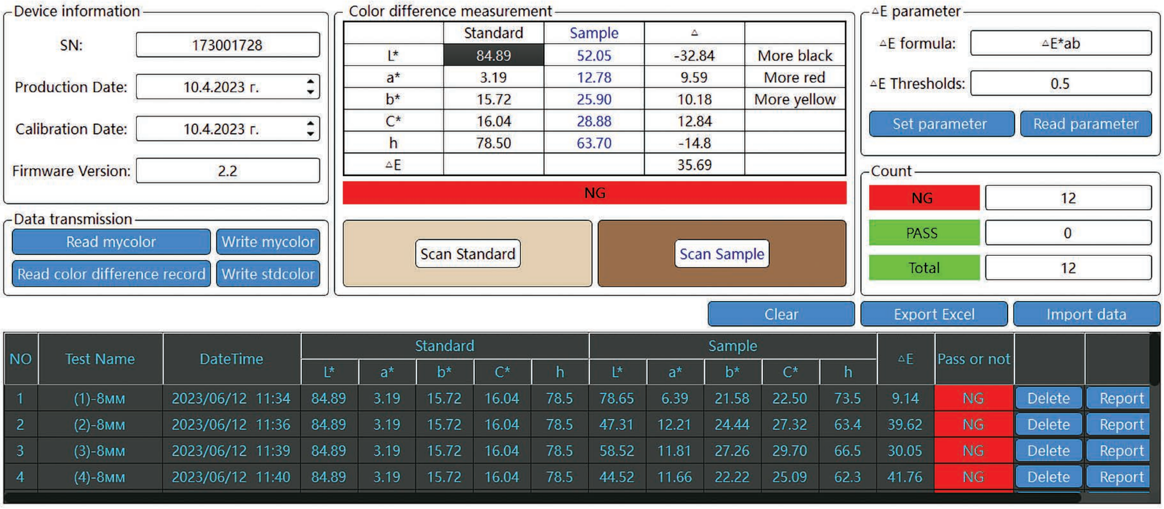

Figure 9 Results after measurement with colorimeter LS173 at ΔF = - 8 mm
Slika 9. Rezultati nakon mjerenja kolorimetrom LS173 pri ΔF = - 8 mm

Furthermore, the value of the regression coefficient b_1 increases with increasing position of the laser beam focus (ΔF) over the material being processed, indicating that the influence of the laser beam power on the variation of the total color difference ΔE^* also increases. Similar conclusions were reached by Gurau *et al.* (2017), who investigated color changes in beech wood under the interaction of a focused laser beam with a power of 5.2 W to 6.8 W.

Figures 10, 11 and 12 present graphically the variation of the total color difference ΔE^* as a function of the laser beam power (P) at different laser beam feed rates (V_f) for the three experimental focus positions above the material surface ΔF, respectively: Figure 1 – at ΔF = - 4 mm; Figure 2 – at ΔF = - 6 mm and Figure 3 – at ΔF = - 8 mm.

Through these graphs, comparisons of shades in the discoloration of plywood can be made, as the differences between them are specified with delta values.

The small value of ΔE^* means that the shades in the discoloration of the plywood are close to each other.

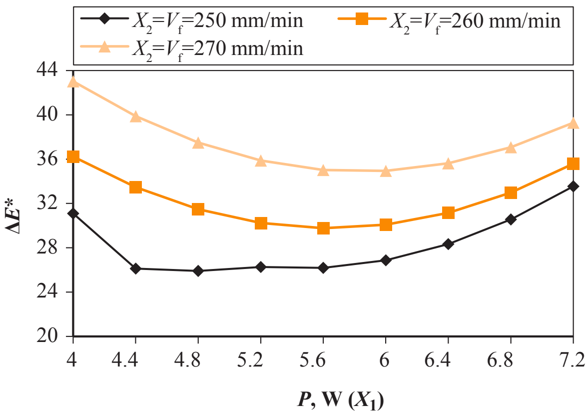

Figure 11 Variation of total color difference ΔE^* depending on laser beam power (P) at different feed rate of laser beam (V_f) and at focus position ΔF = - 6 mm
Slika 11. Varijacija ukupne razlike u boji ΔE^* ovisno o snazi laserske zrake (P) pri različitim brzinama pomicanja laserske zrake (V_f) i u položaju fokusa ΔF = - 6 mm

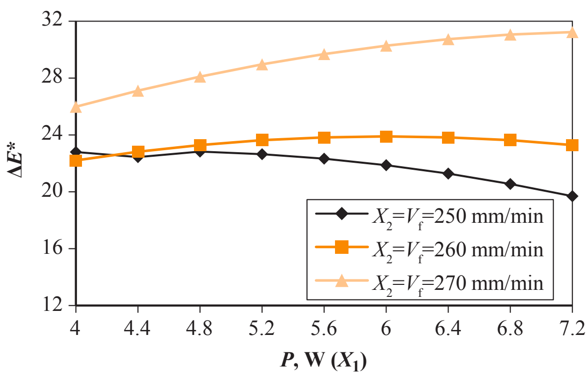

Figure 10 Variation of total color difference ΔE^* depending on laser beam power (P) at different feed rate of laser beam (V_f) and at focus position ΔF = - 4 mm
Slika 10. Varijacija ukupne razlike u boji ΔE^* ovisno o snazi laserske zrake (P) pri različitim brzinama pomicanja laserske zrake (V_f) i u položaju fokusa ΔF = - 4 mm

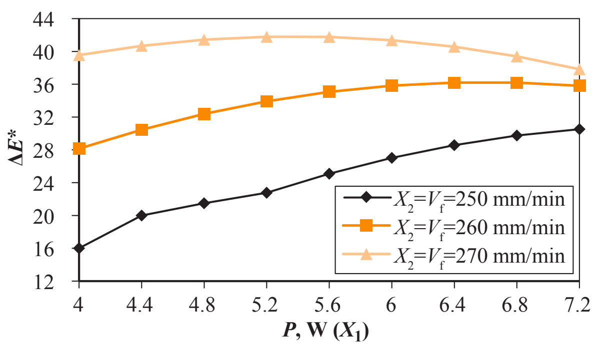

Figure 12 Variation of total color difference ΔE^* depending on laser beam power (P) at different feed rate of laser beam (V_f) and at focus position ΔF = - 8 mm
Slika 12. Varijacija ukupne razlike u boji ΔE^* ovisno o snazi laserske zrake (P) pri različitim brzinama pomicanja laserske zrake (V_f) i u položaju fokusa ΔF = - 8 mm

From the graphs in Figures 10-12, it can be clearly seen that the difference between the shades in total color difference Δ*E** in plywood discoloration is greatest at the highest feed rate of the laser beam (V_f = 270 mm/min).

At the focal position Δ*F* = - 4 mm, the value of the total color difference Δ*E** increased with increasing laser power (*P*) for the entire power interval studied at scanning speeds from 260 to 270 m/min, with a decreasing trend at 250 m/min (Figure 10).

As the position of the focus above the material surface (Δ*F*) increases from - 4 to - 6 mm, the value of the total color difference Δ*E** decreases with increasing laser beam power in the range from - 4 to - 6 W and starts to increase back with increasing power above 6 W (Figure 11). At the focal position Δ*F* = - 8 mm (Figure 12), a similar trend of the variation of the total color difference curves ΔE* with that at Δ*F* = - 4 mm was observed.

Figures 13, 14 and 15 show graphically the variation of the total color difference Δ*E** depending on scanning speed (V_f) at different laser beam power (*P*) for the three selected focus positions Δ*F*: Figure 13 – at Δ*F* = - 4 mm; Figure 14 – at Δ*F* = - 6 mm; Figure 15 – at Δ*F* = - 8 mm.

As the scanning speed V_f increases, the total color difference Δ*E** also increases, and this is most pronounced at the focus position Δ*F* = - 8 mm above the material surface.

Figure 15 shows the variation of the lightness *L**, relative to the reference color (standard) depending on the position of the focus above the material surface (Δ*F*).

The measured *L** axis value (lightness) of the standard (reference) sample depending on the focal position ranged from 81.7 % to 84.9 % with the difference to absolute white (100 %) ranging from 18.3 % to 15.1 %. It can be seen from this figure that the resulting values for *L** of the treated samples for Δ*F* = - 4; - 6 and - 8 mm are close to those of the standard sample and less than 1.0, which is imperceptible to the human eye. Even if there are differences in hues based on numerical values, to the human eye they are one color and changes in hue contrast when building complex graphic images will be difficult to notice.

With increasing the laser beam power, the value of *L** decreases and the material surface becomes darker, which is consistent with Petutschnigg *et al.* (2021)

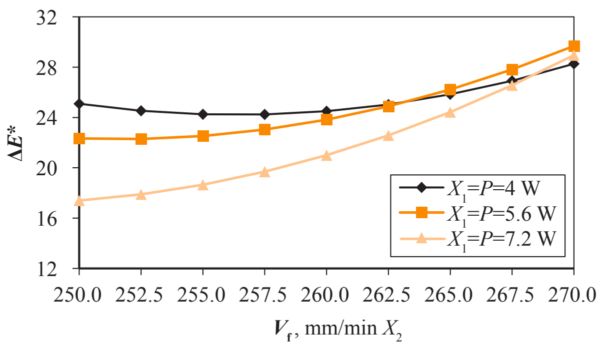

Figure 13 Variation of total color difference Δ*E** depending on laser beam feed rate (V_f) (*P*) and at focus position Δ*F* = - 4 mm
Slika 13. Varijacija ukupne razlike u boji Δ*E** ovisno o brzini pomicanja laserske zrake (V_f) pri različitim snagama laserske zrake (*P*) i u položaju fokusa Δ*F* = - 4 mm

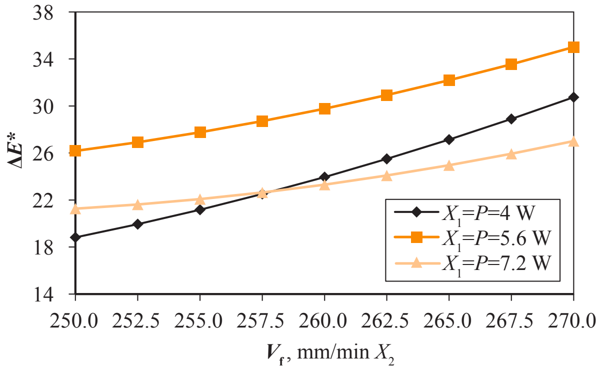

Figure 14 Variation of total color difference Δ*E** depending on laser beam feed rate (V_f) at different laser beam power (*P*) and at focus position Δ*F* = - 6 mm
Slika 14. Varijacija ukupne razlike u boji Δ*E** ovisno o brzini pomicanja laserske zrake (V_f) pri različitim snagama laserske zrake (*P*) i u položaju fokusa Δ*F* = - 6 mm

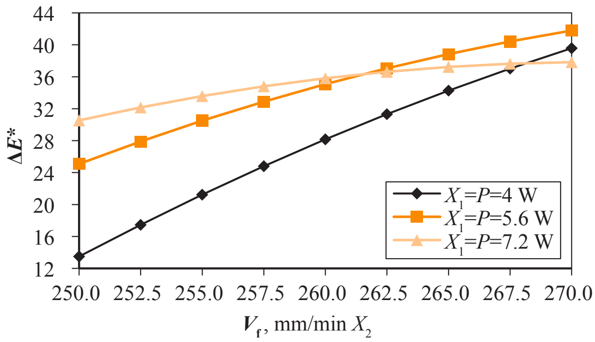

Figure 15 Variation of total color difference Δ*E** depending on laser beam feed rate (V_f) at different laser beam power (*P*) and at focus position Δ*F* = - 8 mm
Slika 15. Varijacija ukupne razlike u boji Δ*E** ovisno o brzini pomicanja laserske zrake (V_f) pri različitim snagama laserske zrake (*P*) i u položaju fokusa Δ*F* = - 8 mm

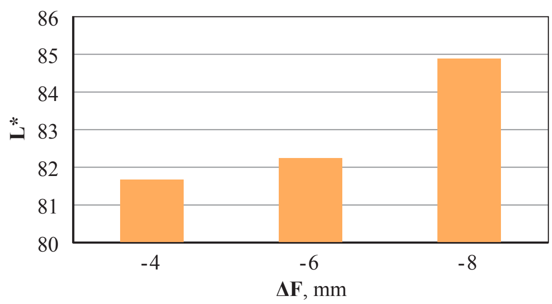

Figure 16 Variation of lightness *L** on workpiece surface depending on focus position above material surface (Δ*F*)
Slika 16. Varijacija svjetline *L** na površini obratka ovisno o položaju fokusa iznad površine materijala (Δ*F*)

and other authors. The laser beam focused on the surface of a material has a higher power density, which results in immediate sublimation and burning of the wood and its darkening to a dark brown color. The unfocused laser beam has a lower power density and acts on the material for a longer period of time, creating the conditions for the carbonization process to begin; black carbon is then formed on the surface of the wood and the shade changes to a deep black color (Jurek *et al.,* 2021). This is confirmed by the measurements made for the color change of the birch plywood surface in the L^* axis – lightness.

At ΔF = - 4 mm, ΔF = - 6 mm and ΔF = - 8 mm, the average results obtained were L^* = 64.6 (81.7 – reference sample value), L^* = 53.4 (82.2 – reference sample value) and L^* = 52.1 (84.9 – reference sample value), respectively (Figures 7, 8 and 9). As is known, L^* represents lightness from black to white on a scale of zero to 100. The average of the measured results that were obtained for L^* at the position of the beam focus on the surface for birch plywood samples (ΔF = 0 mm) were L^* = 72.18 (87.4 – reference sample value) (Gochev and Vichev, 2022).

4 CONCLUSIONS
4. ZAKLJUČAK

The study of the engraving process of wood and WBM, with a CO_2 laser beam, not only at the position of the focus on the surface of the material, but also at different positions above the surface of the engraved material, will allow to expand the diversity in the construction of complex graphic images - photography type, as well as to increase the effect in their perception by the human eye.

The presented results show the changes in discoloration of the plywood samples from the areas exposed to the laser beam at 100 % of the set power. As can be seen in Figures 4, 5 and 6, the variation in discoloration is extremely large when the laser beam power is changed from 100 % to 5 % in steps of 5 %.

This determines the necessity of in-depth research in this field in order to be able to propose the most rational regimes for engraving wood and WBM and achieve the maximum effect in the building of complex graphic images.

In order to control the engraving process when building complex graphic images, small differences or variations in the discoloration of the plywood samples must be able to be identified, i.e. it should be possible to choose the limit of acceptable difference between the color we want to achieve and its values in the actual laser engraving process.

In the future, research will be focused on changes in color shades for each impact zone in Figures 4, 5 and 6 with laser beam power other than 100 % and the development of focusing models for constructing complex photographic images.

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