ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 64(2): 77−86, 2022
Zvolen, Technical University in Zvolen
DOI: 10.17423/afx.2022.64.2.08

COLOUR MODIFICATIONS IN PLYWOOD BY DIFFERENT MODES OF CO_2 LASER ENGRAVING

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ABSTRACT

The results of a study on the processes of laser surface treatment of plywood samples are presented in the paper. The change in colour when exposed to CO_2 laser beam under different exposure modes, was studied with an SC-30 calorimeter. The difference in colour shades of plywood samples was measured in the colour space L*, a* and b*. The results allow researchers to offer modes for surface treatment with the laser beam in the construction of complex graphic images on plywood products.

Key words: CO_2 laser beam, calorimeter, colour space, plywood, surface treatment

INTRODUCTION

CNC machines for CO_2 laser cutting and engraving are becoming more and more popular not only among companies from the woodworking and furniture industry (WWFI), but also among individual and small producers of wood products and wood-based materials (WBM).

CO_2 laser devices with low power, up to 80 W, are compact and can be placed and used in small workshops, even at home. The modern market gives a wide choice of machines with an affordable price, which is influenced by many factors, but there are Chinese machines on the market with a power of 40 W to 150 W, with a price of 1 000 to 6 000 EUR.

The electromagnetic radiation of the CO_2 laser beam, with a wavelength of 10.6 μm, is absorbed by the wood and WBM from 80% to 90% and is transformed into thermal energy capable of instantly heating and vaporizing the surface layer of the material (in the case of an unfocused laser beam) or cut it (with a focused laser beam) (GOCHEV 1996).

Laser engraving is a process in which, as a result of the carbonization of wood, a part of the surface layer is removed, at a certain width and depth. By controlled variation of the parameters of the laser radiation, even very small images and inscriptions can be engraved, but with great precision in detail, and amazing results can be achieved with exceptional levels of contrast, creating an almost three-dimensional effect.

The literature provides different information on engraving or decorating with a CO_2 laser beam, as well as with semiconductor lasers and it changes in the color of wood from maple, beech, oak, ash, linden, spruce, lime, etc. tree species (KUBOVSKÝ *et al.* 2009; PETUTSCHNIGG *et al.* 2013; GURAU *et al.* 2017; VIDHOLDOVÁ *et al.* 2017; KUBOVSKÝ *et al.* 2018; SIKORA *et al.* 2018; JUREK *et al.* 2021 and others).

A number of publications have investigated the effect of laser power intensity on the resulting modification of the engraved material (PAGANO *et al.* 2009; ELTAWAHNI *et al.* 2013; HERNÁNDEZ-CASTAÑEDA *et al.* 2011; MARTINEZ-CONDE *et al.* 2017; KÚDELA *et al.* 2020). However, the color change created by the impact of the laser beam does not depend only on the intensity (power) and profile (cross-section) of the laser beam. The impact of the environment (air) also has an influence on the colour shades of the material. Therefore, the type of wood, its temperature (and the ambient temperature), its humidity (and the ambient humidity), the hardness and the current chemical composition of the engraved layers (the age of the wood and its surface treatment) are also important for colour change.

The aim of the present work is to study the influence of the CO2 laser beam parameters, power and scanning speed, on the changes in the colour of birch plywood samples and its use in the engraving of complex graphic images, based on which to formulate the relevant conclusions and recommendations.

MATERIALS AND METHODS

The experimental studies were carried out with a FormaTec CO2 laser machine, model K40 (China) (Fig. 1).

Fig. 1. CO_2 laser machine for engraving and cutting.

The changes that occur in the colour of the surface layer of the material were studied on plywood samples – common birch (*Betula pendula* Roth.) with dimensions 200 x 200 x 3 mm, density $\rho = 400$ kg/m^3 and humidity W = 6%.

The selection of initial parameters and levels of the variable factors influencing the changes in the colour of the surface layer of the studied material is based on the analysis of literature studies and preliminary experimental studies. The dispersion analysis methodology was used to evaluate the results of the two-factor experiment (VUCHKOV *at. al.* 1986). The regression equation for two variation factors is of the form

$$y_{pr.v.} = b_o + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 \quad (1)$$

Where: $y_{pr.v}$ is the predicted value of the output quantity;

b_o – coefficient before the free member;

b_1 and b_2 – coefficients before the linear member; b_{11} and b_{22} – coefficients before the non-linear members of the equation.

The values of the variable factors – power of the laser beam (P, W) and speed of scanning (feed) of the laser beam (V_f, mm/s) in explicit and coded form are given in table 1.

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

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

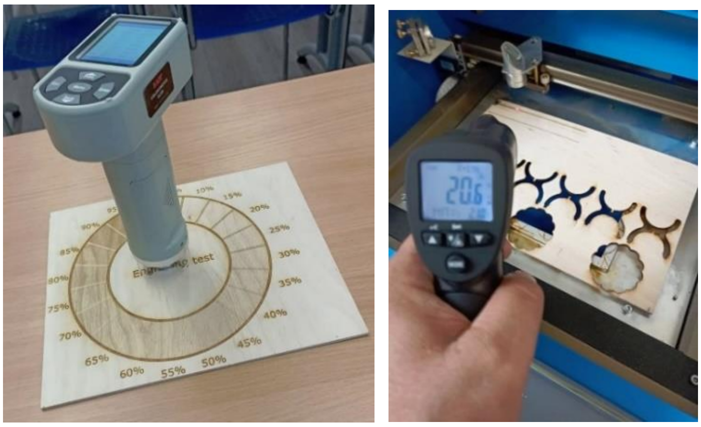
Tab. 2. The matrix of the planned two-factor experiment.

№ 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

To measure the difference in colours of a standard sample (without laser exposure) and on the examined sample (after exposure to a laser beam) a portable colorimeter for colour difference, model SC-30 (China) was used, shown in Fig. 2A. The device allows measurements in two colour spaces *L*a*b** and *L*c*h**. To measure the temperature in the scanning area of the laser beam, an IR-thermometer, model KIRAY for non-contact measurement of surface temperature, shown in fig. 2B.

RESULTS AND DISCUSSION

The results of the research, according to the matrix of the planned two-factor experiment, are shown in fig. 3.



A B

Fig. 2. A – Colorimeter, model SC-30; B – IR thermometer, model KIRAY 200.

A system of isolated zones with different colours from dark brown to light, approaching the natural colour of birch plywood, is 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/).

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

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

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

Based on the conducted experimental studies and after mathematical processing of the data, with the help of specialized software Q-StatLab, the regression equation was derived

$$Y_1 = 70{,}004-5{,}600X_1+1{,}617X_2+1{,}837X_1^2+1{,}188X_2^2-1{,}450X_1.X_2 \qquad (3)$$

Where: Y_1 is the expected variation in the color shade of the surface of the machined parts, L^* in coded form;

X_1 – the power of the laser beam (P) in coded form;

X_2 – feed rate (V_f) in coded form.

Fig. 3. Results of an engraving test and changes in the colour of birch plywood.

This equation can be used to predict the variation in surface colour, relative to the base colour (standard), as a function of variation in laser beam power (P) and scan speed (V_f).

Table 3 presents the coefficients of the regression equation. From the values of the regression coefficients, it is clear that the power of the laser radiation (b_1 = 5.056) has a greater influence than the two investigated factors, and the second most important factor is the scanning speed factor (b_2 = 2.594).

Figure 4 graphically presents the variation of the value of the L^* axis (illuminance) depending on the power of the laser beam (P) at three different scanning speeds (V_f), and in Fig. 5 – depending on V_f, at different laser beam powers.

As a result of the experimental studies, a regression equation (4) was derived, on the basis of which the total colour difference ΔE^* can be estimated depending on the change in the power of the laser beam (P) and the feed rate (V_f).

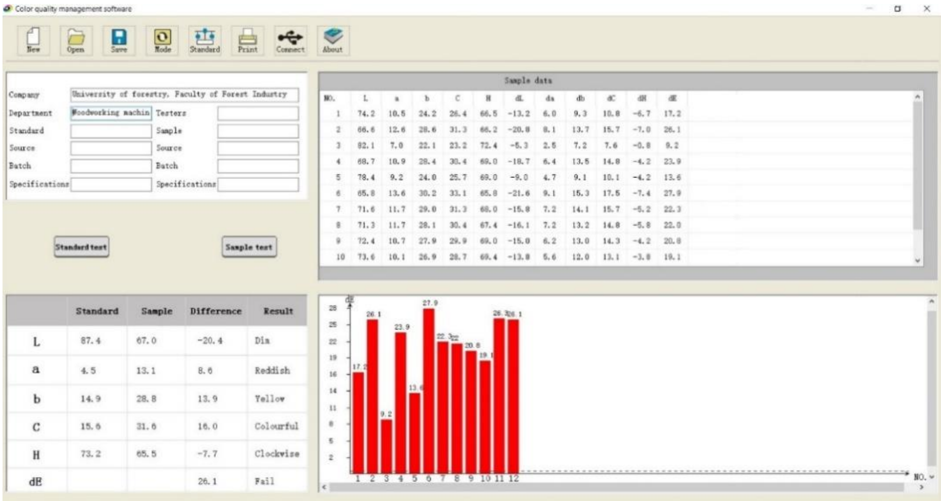


Fig. 4. Results after measurement with colorimeter SC-30.

$$Y_2 = 23.196+6.317X_1-1.750X_2-2.688X_1^2-1.288X_2^2+1.450X_1.X_2 \quad (4)$$

Where: Y_2 is the expected change in the indicator E^* in coded form;

X_1 – the power of the laser beam (P) in coded form;

X_2 – feed rate (V_f) in coded form.

Table 3 presents the coefficients of the regression equation.

Tab. 3. Regression coefficients.

Coefficient	Coded value	Coefficient	Coded value
b_1	5.056	b_{22}	6.597
b_2	2.594	b_{12}	3.734
b_{11}	1.487		

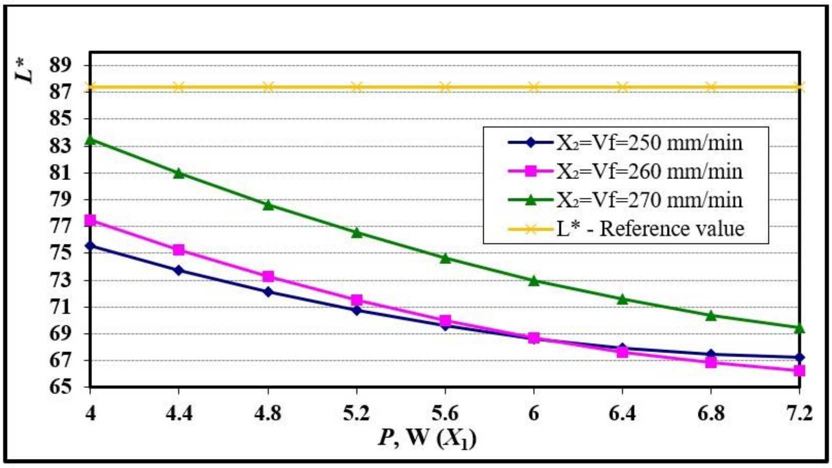


Fig. 5. Graphic representation of L* axis values as a function of laser beam power (*P*) at different feed rates (V_f)

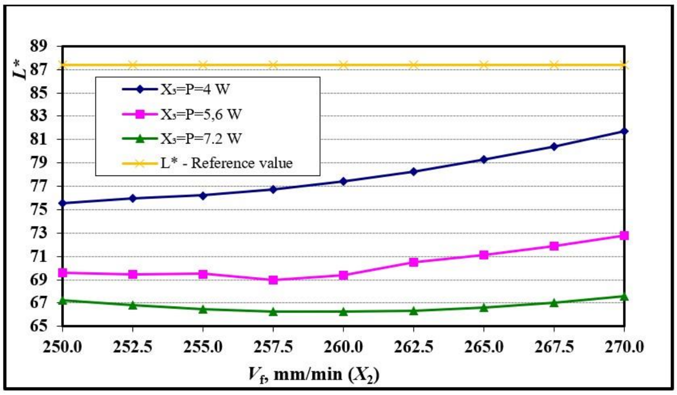


Fig. 6. Graphical representation of *L axis values as a function of scan speed (V_f) at different laser beam powers (*P*)**

The values of the regression coefficients confirm the greater influence of the laser radiation power (b_1 = 6.317) compared to the scanning speed (b_2 = 1.750).

Figure 6 graphically presents the variation of Δ*E** values depending on the power of the laser beam (*P*) at the three different scanning speeds (V_f), and in Fig. 7 – depending on Vf at different laser beam powers.

Tab. 4. Regression coefficients.

Coefficient	Coded value	Coefficient	Coded value
b_1	6.317	b_{22}	1.288
b_2	1.750	b_{12}	1.450
b_{11}	2.688		

The measured value of the *L** axis (luminance) of the standard (reference) sample is 87.4%, the difference to absolute white (100%) is 12.6%.

The *L** axis values (74.2%; 82.1% and 78.4%) are very close to that of the standard sample of 87.4% (№ of the experiment 1; 2 and 3, Fig. 3), i.e., changes in shades when building complex graphic images, photography type will not be well noticeable.

The total colour difference Δ*E** varies significantly with increasing laser beam power with maximum values at № of the experiment 2; 4 and 6 (Fig. 3).

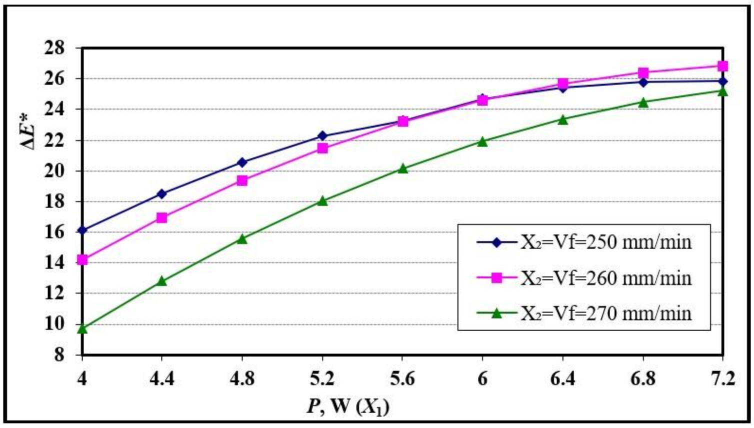


Fig. 7. Graphical presentation of Δ*E values as a function of laser beam power (*P*) at different feed rates (V_f)**

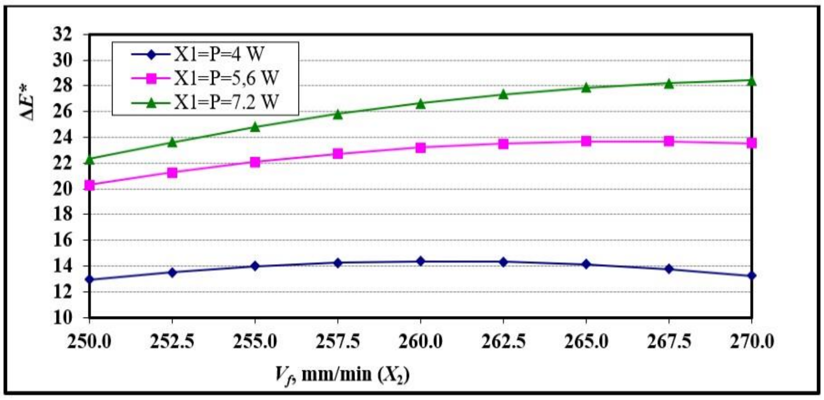


Fig. 8. Graphic representation of the dependence of Δ*E values depending on the scanning speed (V_f) at different laser beam powers (*P*)**

It is known that wood is composed of cellulose, lignin, hemicellulose and extractive substances, which are thermally unstable. The cellulose content in wood reaches up to 50%, and lignin and hemicellulose from 20 to 30%.

Heat transfer in the horizontal direction is carried out by thermal radiation (TR) from the laser beam. The investigated material – ordinary birch plywood – receives the heat in a thin surface layer (1 μm ~ 1 mm) and begins to heat up. Depending on the heat dissipation and the specific heat capacity of the material, the temperature starts to rise, being highest in the surface layer receiving the radiation. Deep in the body, heat spreads through thermal conduction.

Between 120 and 200 °C, in addition to dehydration, the release of non-combustible gases - CO2, formic acid, acetic acid and water vapour begins. At a temperature higher than 120 °C, structural changes begin with the main component of wood - cellulose - destruction, which is accompanied by the formation and release of volatile substances. Above 200 °C, the rate of pyrolysis increases, with hemicellulose (200-260 °C) decomposing first, followed by cellulose (240-300 °C) and finally lignin (280-500 °C) (*Poletto et al. 2013*).

At the focus point, the laser beam has the greatest density and falling as a TR, the greatest accumulation of heat is concentrated perpendicular to the processed material and, accordingly, the fastest rise in temperature. It is in the area of this point that the processes related to heating the material and the structural changes that occur in it, related to a change in the colour of the surface layers and pyrolysis processes take place first.

The measured temperatures in the scanning area of the laser beam using an IR-thermometer (Fig. 2B) were in the range of 210 to 290 °C. This interval corresponds to the thermal decomposition of hemicellulose and cellulose and the initial stage of lignin decomposition.

The change in colour of the surface layers of the plywood, resulting from the degree of their carbonization, is also influenced by the contact with air and the O_2 content.

Figure 8 shows variants of complex graphic images, type of photography at different power and scanning speed of the laser beam.

A B

Fig. 9. Variants in building a complex graphic image, type of photography: A – P = 5.6 W and V_f = 260 mm/s; B – P = 7.2 W and V_f = 270 mm/s.

CONCLUSION

As a result of the conducted research and analysis, the following more important conclusions and recommendations can be drawn:

1. CIE $L^*a^*b^*$ colour analyses show a gradual darkening of the laser-treated samples with increasing laser beam power, the influence of which is more pronounced than the scanning speed.
2. The L^* axis values, at laser beam power ≤ 4 W and scan speeds of ≥ 250 mm/s, are very close to that of the standard sample of 87.4%, i.e. changes in shades when building complex graphic images, photography type, will not be well noticeable.
3. The L^* (illuminance) axis values show the most significant variation at laser beam power P = 7.2 W and scan speeds from 250 to 270 mm/s, which correspond to dark brown.
4. Larger values of laser beam power produce a greater degree of carbonation and colour saturation, while smaller values produce a lighter shade in the graphic layout of complex photographic images.
5. The measured temperatures in the scanning area of the laser beam are in the range of 210 to 290°C. This interval corresponds to the thermal decomposition of hemicellulose and cellulose and the initial stage of lignin decomposition.
6. According to the specifics of the material, the engraved image becomes more pronounced and detailed, or in other cases fainter. Depending on the desired effect and contrast, the operating modes of the machine are selected.
7. The colour change created by the effect of the laser beam on the wood also depends on the effect of the environment (air and O_2 content), which is recommended to be investigated.
8. The focal distance of the focusing lens and the position of the focal plane of the focusing lens relative to the surface will have an influence, from here and on raster density. They will be the subject of further research.

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ACKNOWLEDGEMENTS:

This paper is supported by the Scientific Research Sector at the University of Forestry – Sofia, Bulgaria, under contract № НИС-Б-1046/05.04.2021.

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