ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 66(2): 89−101, 2024
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2024.66.2.08

SELECTING COLOR OF MOSAIC PATTERN ELEMENTS FOR LASER ENGRAVING ON WOOD

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ABSTRACT

The research results of color change during laser engraving on the wood of six species: aspen, pine, larch, birch, beech, and spruce, are presented in the paper. The values of color coordinates are measured in the Lab system on test strips with the template grey color gradient changing from white to black. Depending on the template resolution, three distinctive regions are observed. The natural wood color is preserved with the resolution increase in the first region; the wood surface gradually gets darker, reaching the tone limit in the second one, and lighter due to the light reflection in the third. The method for selecting the color of mosaic pattern elements, providing the matching of the color of the original elements and the image engraved on wood, is proposed based on the research results.

Keywords: wood; laser engraving; color; computer template; mosaic pattern.

INTRODUCTION

In the process of laser thermal modification of wood surface, the radiation energy is converted into heat energy, causing chemical and structural transformations in wood, thus leading to changes in significant properties of the surface layer, such as color, roughness, water repellency, biological resistance, etc. (Babiak *et al.,* 2004; Kubovsky and Kačik, 2013; Vidholdova *et al.,* 2017; Gurau *et al.,* 2017; Li *et al*., 2018; Kudela *et al*., 2019; Zykova *et al*., 2021). The extent of changes in wood property depends on its species and absorbed energy density Wp (Chernykh *et al.,* 2022):

$$Wp = Pc *t/s*(1-Ko), J/cm^2 \quad (1)$$

which is defined by the average pulse radiation power Pc, time t for radiating the region with the area s and coefficient of reflection (Ko) of laser pulse by wood. In turn, the average pulse radiation power Pc:

$$Pc= Pi*\tau*f \quad (2)$$

depends on the pulse power Pi, pulse duration τ and pulse repetition frequency f. The values of factors indicated in the formulas (1) and (2) are specified by the processing mode

– pulse power Pi (set up in percent from the maximum laser power P max), laser head movement speed V, focal distance l and raster density (Kudela *et al*., 2019). The raster density is defined by the laser machine resolution R (Petutschnigg *et al*., 2013, Zykova *et al*., 2021) and template resolution N (Yakimovich *et al.*, 2016).

The change in the template resolution with constant values of other processing mode factors (Pi, V, l and R) results in the changed pulse repetition frequency f (envisaged by software for laser machines); consequently, – in the changed average pulse radiation power Pc and properties of the surface processed by the laser, including the coloristic ones (Chernykh and Yapparova, 2012; Yakimovich *et al*., 2016; Zykova *et al.*, 2021, Evdokimova *et al*., 2023).

The practical use of the results of investigating the color of wood modified by laser is discussed in a number of papers. Thus, Petutschnigg *et al*., 2013 substantiated the selected color and design of ski cores of beech wood. In order to preserve the cultural heritage in the conditions of hi-tech processing method application, Lungu *et al*., 2022 defined the color correlation on maple furniture parts engraved by laser similar to the correlation of colors of the national Rumanian ornament traditionally embroidered on elements of clothes. Jurek and Vagnerova *et al*., 2021, Gochev and Vitchev 2022, Chernykh *et al*., 2022, Evdokimova *et al.*, 2023 applied the results of the color research for making photographs and landscapes on plywood, boards and veneer of beech and birch wood. Based on the research results, Chernykh *et al*., 2018 designed and produced wall panels with marine landscapes made of the veneer of five wood species: beech, pine, chestnut, mahogany and sapele. Thus, the tendency in a growing number of works with the practical use of the research results aimed at studying the color of wood modified by laser is evident. The design of products based on the color research results requires the involvement of designers.

On the one hand, for successful work a designer needs information about the color range obtained from one or another wood species processed on a certain laser machine. On the other hand, a laser machine operator needs to know the processing modes providing the colors set up by the designer on the wood. The paper discusses an option for solving this problem. It was suggested to engrave the test strip with a gradient of tone on the samples, also to determine the integrated coordinates in the CIE Lab system at the test strip length, highlight visually different parts and use them in the process of developing design for a layout.

MATERIALS AND METHODS

Two types of images are reproduced by laser on wood and wooden materials – half-tone ones conveying the original three-dimensionality (usually photographs) due to the tone gradient (Jurek *et al.*, 2021, Gochev and Vitchev 2022), and mosaic ones, in which the image is split into regions with the same tone within a certain region (Chernykh and Yapparova 2012; Lungu *et al*., 2022). Although the color of the image engraved on wood differs from the original color, the correlations of tones are preserved between the image elements. Therefore, the original contrast and pseudo-volume are reproduced on the product.

To correct the half-tone template, the designer needs only the information on lightness L or optic density D of the wood species to be engraved, better of the workpiece to be engraved (to eliminate the influence of unstable properties, such as moisture content, age, hardness), and its tone limit. Having this information, the designer sets up the highest and the lowest template brightness (Evdokimova *et al*., 2023). Moreover, the information should correspond to those engraving mode values, which will be further used for manufacturing the product. The laser machine operator sets up such values either based on the work experience or takes them from well-known sources, for example, the range of rational values of P_i and V for beech wood, providing the reproduction of the whole range of the possible tone of the surface engraved (from light to dark), is given in Yakimovich *et al.*, 2016.

In contrast to half-tone images, two template design options are possible when engraving mosaic images – based on the known original, for example, embroidery on fabric (Lungu *et al.*, 2022) and the template made by a designer in computer programs. In both cases, the designer needs to know the whole color visual range of the surface to be engraved – from the wood natural color to the tone limit corresponding to it – when the further increase in the absorbed power Wp results not in the surface darkening but in its lightening (Kudela *et al.*, 2019). Since the color is defined by the absorbed power, which depends on the processing mode - Pi, V, l, R, and N factors - for the designer's convenient work, it is necessary to minimize the number of variable factors using the rational values of most of them. We believe it is practicable to decrease the number of variable factors to one, selecting the template resolution N as such. It can theoretically vary from 0 up to 255 dpi or from 0 up to 100% of the black color of the monochromatic scale. In fact, the N range is even narrower since the minimum N value is defined by the natural color of the wood species and the maximum one – by its tone limit. At the same time, a definite color of the engraved surface corresponds to each N value at constant values of other factors.

Samples of six wood species were used to check the proposed approach based on using the color visual range: aspen (*Populus tremula*), pine (*Pinus sylvestris*), larch (*Larix decidua*), spruce (*Picea abies*), beech (*Fagus sylvatica*) and birch (*Betula populifolia*).

The samples were shaped as blocks with the dimensions 20×20×300 mm, tangential section, and longitudinal direction of fibers. The surface was planed on a planer before engraving.

The samples moisture content: 12%.

Test strips were engraved on the samples using the grey computer template with resolution N uniformly increasing from 0 up to 255 dpi or from 0 up to 100% of black color (Figure 1). The samples with the engraved test strips are demonstrated in Figure 2.

Fig. 1 The template of the test strip with grey gradient.

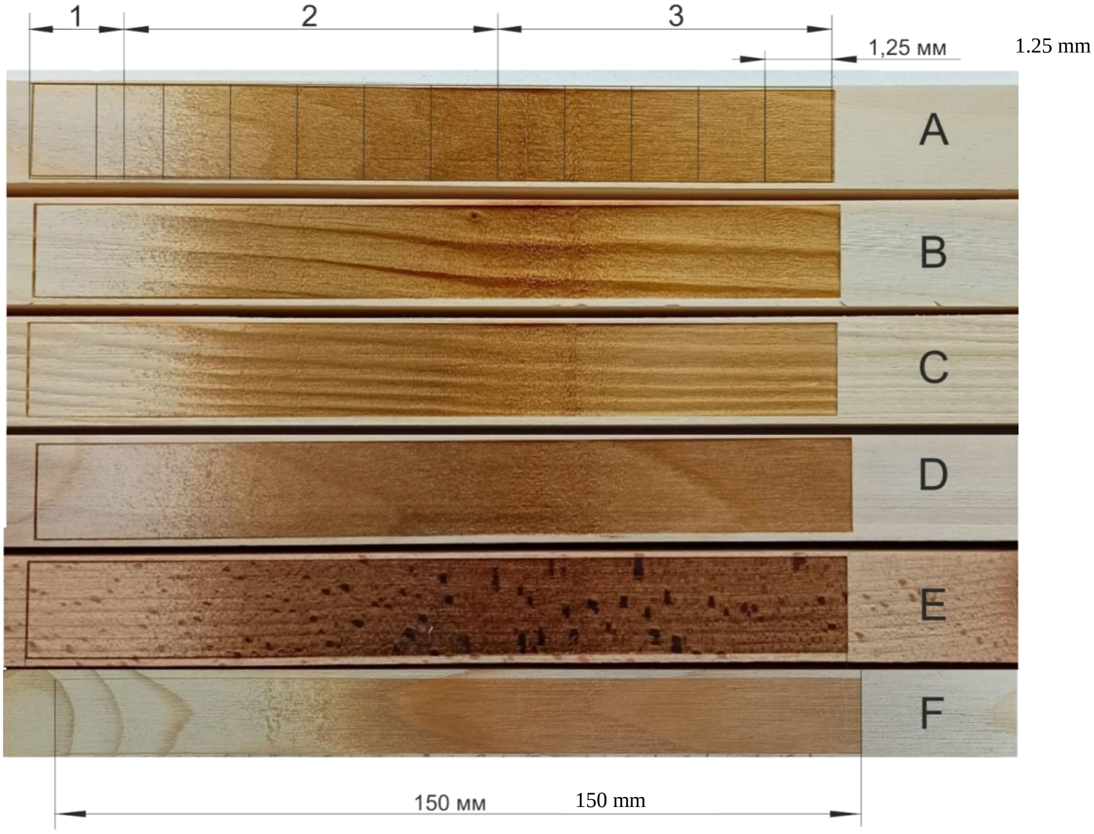

Fig. 2 The samples with the engraved test strips of the template: A) aspen; B) pine; C) larch; D) birch; E) beech; F) spruce; the distinctive regions are marked on the samples: 1 – the first region with the natural color preserved during the engraving; 2 – the second region with the active tone intensification; 3 – the third region with the tone lightening.

Equipment:

Laser CO_2 marker with CNC GCC Synrad (USA), 30W.

The engraving power P_i was 4.5W, the speed V – 1000 mm/sec, the resolution R of the laser machine – 600 dpi, the focal distance l – 300 mm, the focal plane position coincided with the surface engraved.

The color of the modified wood is usually measured in Lab color coordinates (Dzurenda 2014, Kudela *et al.*, 2019), in some works CMYK color models were successfully applied (Yakimovich *et al.*, 2011, Zyrova *et al.*, 2021) and RGB (Safin *et al.*, 2015). It is believed that Lab color system is mostly appropriate to a human's visual perception, therefore, we used Lab system in this work.

The color coordinates L, a, b and optic density D of the samples were measured in twelve points along the test strips with the step 1.25 mm, five measurements in each point. The measurements were made by spectrophotometer GretagMacbeth "Eye-One Pro" (Switzerland) (Figure 3) and processed in computer programs.

Fig. 3 Spectrophotometer GretagMacbeth "Eye-One Pro": 1 – measuring device; 2 – platform; 3 – light source; 4 – white plate; 5 – Mini Display port for PC connection.

RESULTS AND DISCUSSION

The research results are given in the graphs (Figures 4, 5 and 6) and in Tab. 1, 2 and 3. The color coordinates L, a, b and optic density D change similarly in all wood species, some difference is observed in the beech sample.

Tab. 1 The results of measuring coordinates L, a, b, and template resolution N on the samples of different wood species

No	Species	Color coordinates	The template color resolution N, %											
			5	9	17	24	34	44	53	63	73	82	90	96
1	Aspen	L	85.18	84.06	71.76	58.66	53.48	49.98	44.32	42.64	53.58	58.38	61.98	64.76
		a	2.16	2.52	7.30	10.12	10.30	10.96	11.30	10.74	11.36	10.46	9.80	9.34
		b	16.48	17.40	26.92	30.64	30.34	30.40	29.20	27.58	32.20	32.38	32.48	32.18
2	Pine	L	83.60	81.62	65.52	58.72	51.02	51.42	47.48	46.78	61.40	61.98	61.98	62.96
		a	2.68	3.96	8.82	9.68	9.96	11.12	12.94	13.06	10.28	10.30	10.30	9.98
		b	17.48	20.62	27.88	28.88	28.90	30.02	32.16	32.48	32.82	32.60	32.62	31.76
3	Larch	L	80.70	79.34	69.06	56.90	54.00	52.20	53.12	53.22	58.60	61.26	63.04	62.70
		a	3.10	3.48	7.58	10.04	10.42	10.68	11.16	11.12	10.56	9.70	9.70	9.96
		b	18.94	20.08	26.32	28.24	28.60	28.28	29.58	30.26	30.92	30.06	30.44	30.64
4	Birch	L	76.18	77.42	66.34	52.86	48.32	43.78	43.20	45.98	50.76	54.22	53.00	53.72
		a	6.54	6.16	9.38	11.18	11.36	11.34	12.54	12.62	11.94	12.12	12.14	12.28
		b	19.74	18.98	23.70	25.64	25.22	24.52	26.70	27.42	27.68	28.46	27.72	27.86
5	Beech	L	73.50	71.36	59.36	46.62	41.06	35.76	35.34	34.82	39.32	42.66	42.58	44.98
		a	9.14	9.42	11.76	12.44	11.56	10.88	11.90	11.68	12.10	12.68	12.66	12.76
		b	22.24	21.86	23.28	22.32	20.12	17.74	18.74	19.22	21.02	22.40	22.02	22.84
6	Spruce	L	79.10	77.42	64.82	55.84	54.80	52.16	51.66	50.82	52.48	54.86	56.38	56.18
		a	7.72	8.24	12.08	13.18	13.50	13.30	14.98	15.22	14.74	14.98	14.92	14.80
		b	23.30	24.12	29.34	29.66	31.00	30.36	33.12	33.06	32.30	32.40	33.22	32.30

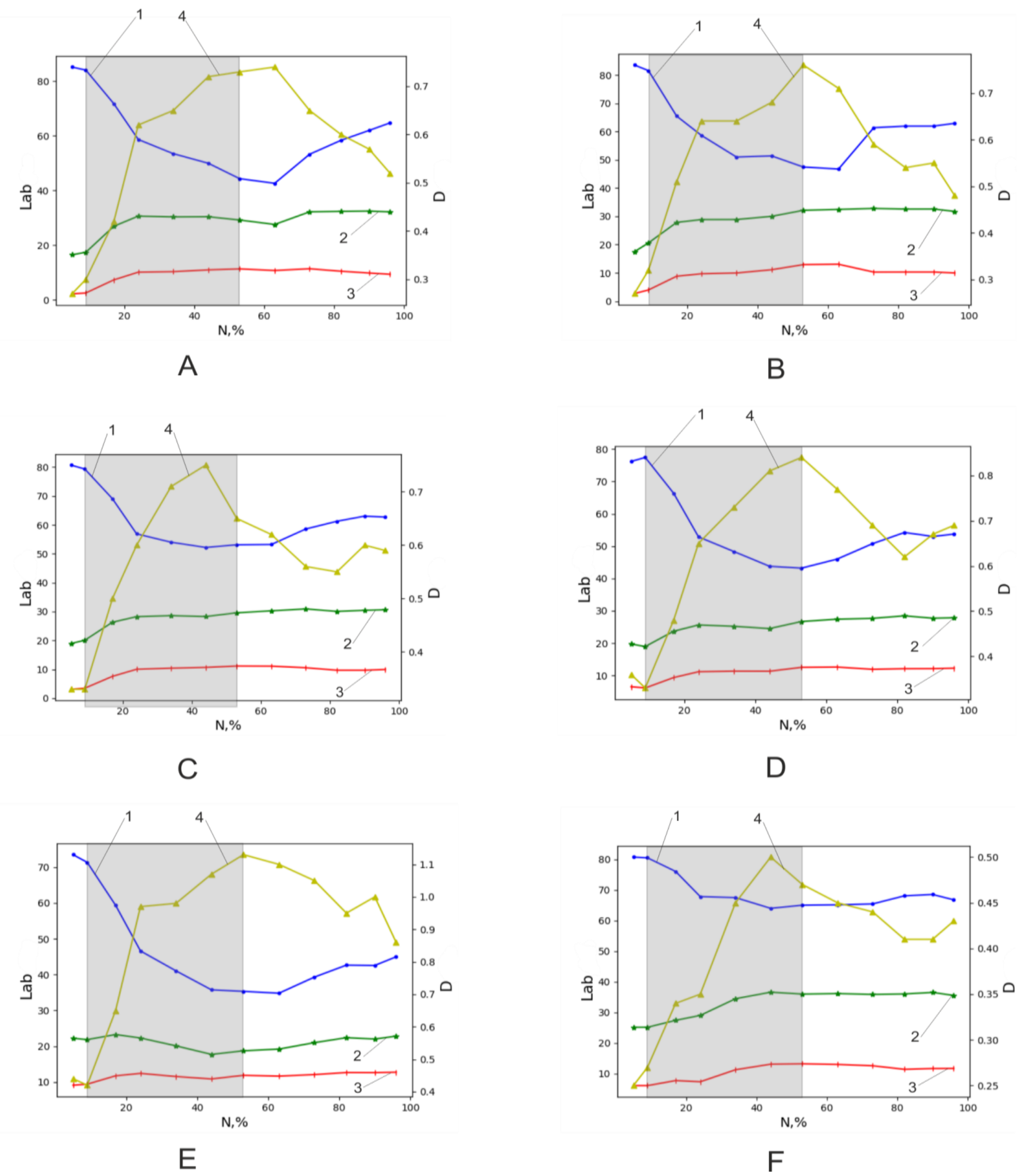

Fig. 4 Dependences of color coordinates L, a, b and optic density D on resolution N for the samples of different wood species: A) aspen; B) pine; C) larch; D) birch; E) beech; F) spruce; 1 – dependence of L; 2 – dependence of b; 3 – dependence of a; 4 – dependence of D; the regions marked with color correspond to the second region of the samples in Figure 2.

Three distinctive regions can be pointed out in the graphs (Figure 4), which comply with the appearance of the engraved test strips (see Figure 2). The natural wood color is preserved in the first region; the wood is heated to the pyrolysis temperature. The gradual wood darkening up to the maximum value of optic density D is observed in the second region, and lightness L decreases to the minimum. The abovementioned indicates the increase in the absorbed power Wp and surface temperature, engraved with the template resolution N growth and, consequently, the pulse frequency f and average power Pc according to the expressions (1) and (2). Some tone lightening is observed in the third region due to the light reflection by the wood carbonized surface (Kudela *et al.*, 2019). The result obtained coincides with the results of works described in Yakimovich *et al.*, 2016; Jurek and Vagnerova 2021; Evdokimova *et al.*, 2023.

The second graph regions marked with the tone in Figure 4 are of practical importance for image engraving, as it is possible to control the color and adequately reproduce the original light-and-dark gradations and pseudo-volume on wood within them (Evdokimova *et al*., 2023).

Out of the investigated wood species, the maximum color change is observed in light species, which coincides with the opinions of Kudela *et al*., 2019, and the authors of some other papers.

Tab. 2 The maximum changes in color coordinates L, a, b in the second region.

Sample	Species	ΔL_{max}	Δa_{max}	Δb_{max}
1	Aspen	40.86	-9.14	-12.72
2	Pine	36.12	-10.26	-14.68
3	Spruce	16.74	-7.12	-11.48
4	Larch	28.50	-8.06	-10.64
5	Birch	32.98	-6.00	-6.96
6	Beech	38.16	-3.30	3.50

Out of the color coordinates L, a, b the lightness L mostly contributes to the color change ΔE during the engraving of wood species investigated (Tab. 2).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{3}$$

Where: ΔL – lightness change relative to the initial one,
Δa – change in the coordinate a,
Δb – change in the coordinate b.

The coordinates a and b change to a lesser extent than the lightness. Nevertheless, they characterize the color gradation (Petutschnigg *et al.,* 2013, Vidholdova *et al*., 2017, Jurek and Vagnerova 2021). In our case, the values of the color coordinates a and b increase with the increased template resolution N and, consequently, the absorbed power W_p (Figure 5) that indicates the color shift of most wood species investigated in this paper and poplar wood (Li *et al*., 2018), to the red-and-yellow region. On the beech sample, the value of the color coordinate slightly increases and coordinate b – decreases, the color shifts to the black region. For the beech, the result in the character of the change in the values of a and b and the range of values in general coincides with the results in Petutschnigg *et al.,* 2013; Vidholdova *et al*., 2017; Kudela *et al*., 2019; Jurek and Vagnerova 2021. Some deviations in numerical values can be explained based on Petutschnigg *et al.,* 2013. Its authors demonstrated that with the simultaneous change in two factors of the processing mode, namely, the pulse power P_i and resolution R of the laser machine, for beech the coordinate a can either decrease or increase and the coordinate b decreases differently.

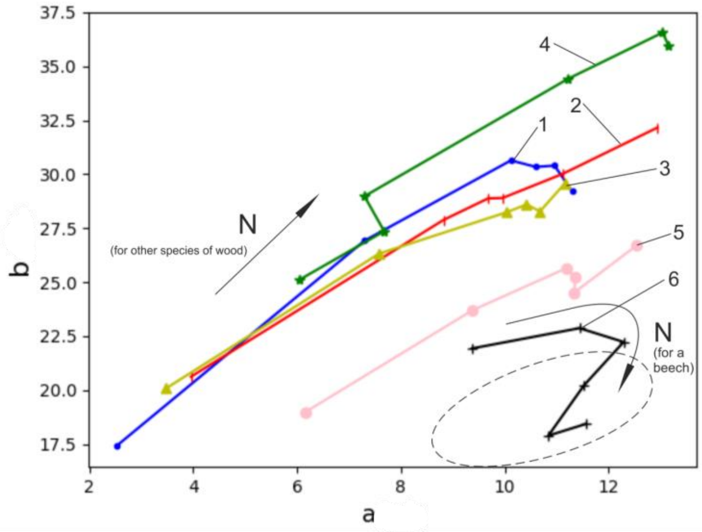

Fig. 5 The change in the values of the color coordinates a and b in the region 2 with the template resolution N increase for the samples of different wood species: 1) aspen (-•-); 2) pine (-|-); 3) larch (-Δ-); 4) spruce (-*-); 5) birch (-O-); 6) beech (-+-). The region of the values of coordinates a and b for the beech wood processed by the laser is rounded with the dotted line based on the research results in Petutschnigg *et al*. 2013.

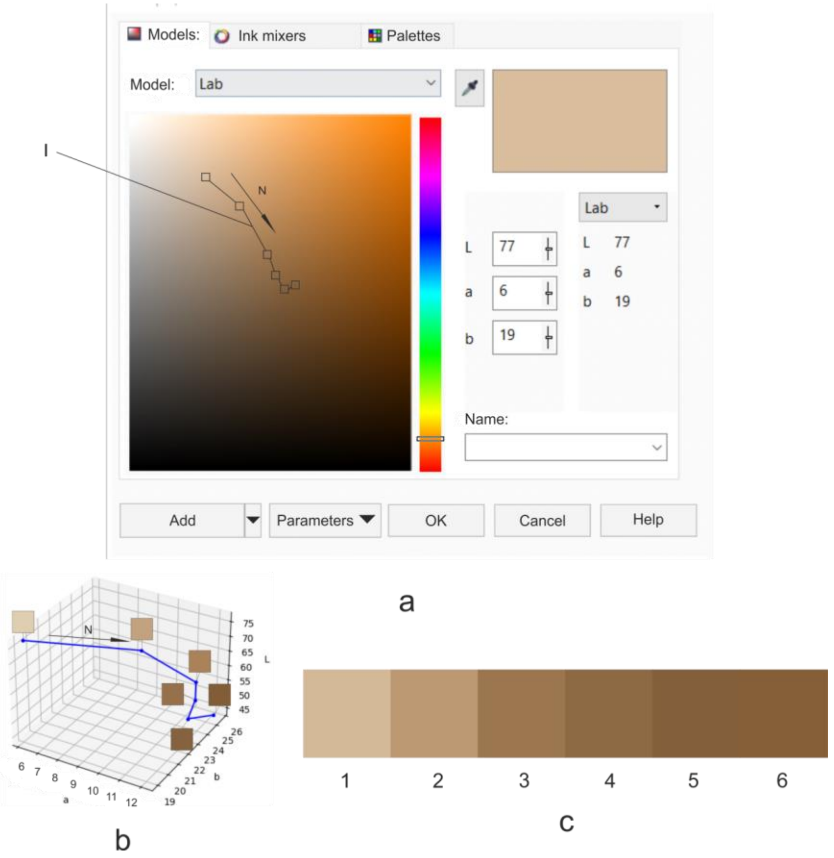

Fig. 6 The change in the integrated colorimetric color index E and color visualization depending on the template resolution N for the birch wood sample: a – the birch wood color change in Lab color range; b – the graphic depiction of the change in the integrated colorimetric index E; c – color discretization; 1-6 – the color number; I – the curve of wood colors in the red-and-yellow spectrum of Lab system.

Using CorelDRAW, it is possible to visualize the whole wood color range by the color coordinates L, a, b – from its natural color, corresponding to the upper left square of the line 1 in Figure 6, a, – to the tone limit, corresponding to the lower right square of the same line. For convenient color selection, it is advisable for a designer to discretize the color gradient, making the gaps between the gradient regions. The discretization step can be found based on the value of ΔE, using the proposal formulated by Allegretti *et al*., 2009 stating that the visually perceived beech wood color change occurs at $\Delta E > 12$. It can be assumed that this is also true for other wood species. The points are marked in the graph of E dependence on resolution N (Figure 6, b) and the color discrete sequence corresponding to these points is given in Figure 6, c.

The discrete sequence obtained was used to prepare the mosaic pattern (Figure 7).

An image of a traditional Chinese dragon was selected as the template sketch. Chinese dragons play an important role in Chinese culture and mythology. They symbolize power, wisdom, and fortune. In contrast to Western dragons, Chinese dragons are usually depicted as kind and well-minded creatures able to control water, rain, and rivers.

A Chinese dragon is often associated with the Emperor's power and is believed to be the people's defender. According to legends, they can bring fertility and prosperity and act as ancient knowledge keepers.

Eberhard, 1952, pointed out that according to Chinese tradition, dragons can have different forms, but they are more frequently depicted with long bodies, horns, and bird' feet. They are one of the main symbols of the Chinese New Year festivities and are also used in different art forms, such as painting, sculpture, and calligraphy.

Using the pattern mosaic elements allows for marking the dragon's scales and imitating its movement due to the different gradations of the element color.

The pattern is made in two variants – with the key line of each element (Figure 7, a) to enhance the contrast and without the key line to soften the contrast (Figure 7, b). The digits on individual elements (Figure 7, c) correspond to the gradations of the birch wood color discrete sequence (see Figure 6, c). The colors from 1 to 5 are used in Figures 7, a and 7, b since the fifth and the sixth colors visually merge. The black-and-white image template is given in Figure 7, d. The maximum and the minimum values of the template element brightness are set up according to the boundary values of the birch wood lightness L in the region 2 (see Figure 4, a and Tab. 1).

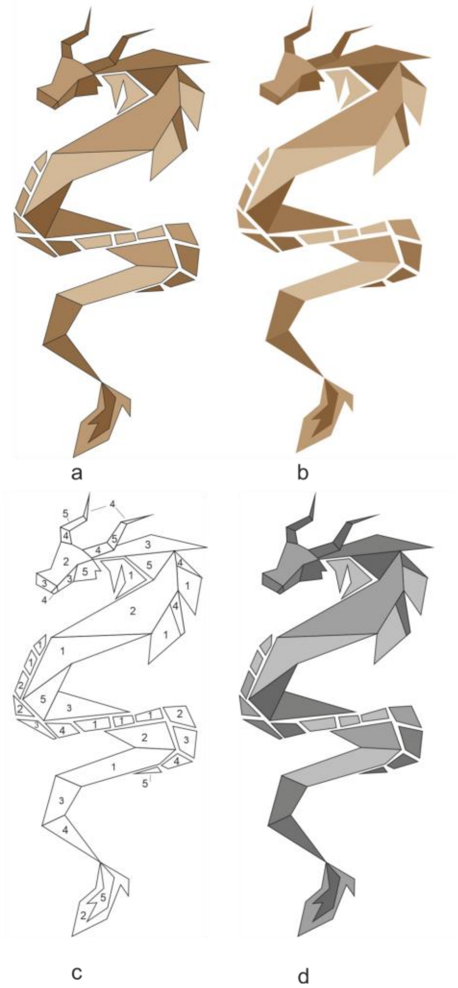

Fig. 7 Images: a – the colored pattern with tone regions with the key line; b – the colored pattern with tone regions without the key line; c – the color number of the elements in Figures 7, a and 7, b; d – the black-and-white template of the image in Figure 7, a.

Fig. 8 Engraved images: a – with the key line; b – without the key line.

The comparison of the color coordinate values of the corresponding regions of the engraved image and original is given in Tab. 3.

The images were engraved on birch wood (Figure 8). The expert assessment of the aesthetic value of the images produced following the technique described in Chernykh *et al*., 2022, demonstrated their equivalence. The contrast, image integrity, and visibility of small elements were taken into account during the expert assessment.

A slight difference in the integrated color coordinate ΔE between the corresponding elements of the original patterns and engraved images (Tab. 3) gives the ground to state that the colors of the mosaic original and engraved image match, and the method worked out is practicable.

To achieve the positive result, it was necessary to combine the knowledge of a designer, a research engineer and a laser machine operator. The practice of combining their competences in one specialist within the bachelor and master study programs “Technology of material artistic processing” is known (Chernykh, M. 2019).

Tab. 3 Values of the color coordinates in the regions of patterns and engraved images

Object	Color coordinates	Region number				
		1	2	3	4	5
Original, Figures 7, a; 7, b	L	77.42	66.34	52.86	48.32	43.78
	a	6.16	9.38	11.18	11.36	11.34
	b	18.98	23.70	25.64	25.22	24.52
Engraved image with the key line, Figure 8, a	$\bar{L}$	73.42	62.36	57.22	52.38	48.12
	$\bar{a}$	8.64	11.24	12.62	11.64	11.32
	$\bar{b}$	27.66	30.26	30.94	27.28	26.84
	$\frac{E_0}{E_i}$	1.01	1.01	0.90	0.93	0.91
	$\Delta E = E_0 - E_i$	1.02	0.85	-6.46	-4.51	-4.81
Engraved image without the key line, Figure 8, b	$\bar{L}$	76.92	63.54	55.20	51.44	46.22
	$\bar{a}$	7.84	11.12	13.02	12.78	11.98
	$\bar{b}$	27.82	31.16	31.18	29.04	26.24
	$\frac{E_0}{E_i}$	0.97	0.99	0.92	0.92	0.94
	$\Delta E = E_0 - E_i$	-2.22	-0.57	-4.92	-4.76	-3.04

Note: E_0 – the integrated color coordinate of figures in each region number; E_i – the integrated color coordinate of each engraved image region number respectively.

CONCLUSION

In recent years, the tendency to increase the number of works with the practical application of the results of color investigation during wood laser engraving has been observed. Applying the research results in practice dictates the need to combine the efforts of a designer and laser machine operators' efforts. On the one hand, for successful work, a designer needs information about the color range obtained from one or another wood species during laser engraving. On the other hand, a laser machine operator needs to know the processing modes, providing the colors set up by the designer on the wood.

The method of designing mosaic images for further laser engraving on wood is proposed, considering the wood coloristic capabilities and the engraving mode.

The method is based on revealing the color range of the wood to be engraved based on the results of the preliminary engraving of the test template with smoothly increasing resolution from the minimum to the maximum one, i.e., from 0 up to 255 dpi or from 0 up to 100% of the black color of the monochromatic scale. The species color range is fixed using a computer program, for example, CorelDRAW, following which a designer selects the colors of each region of the mosaic pattern and forms the computer template. The matching of the original and engraved image colors is achieved.

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ACKNOWLEDGMENT

This publication was created with the financial support of the project: Comprehensive research of mitigation and adaptation measures to diminish the negative impacts of climate changes on forest ecosystems in Sovakia (FORRES), ITMS: 313011T678 (100%) supported by the Operational Programme Integrated Infrastructure (OPII) funded by the ERDF.

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