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COLORISTIC SOLUTION FOR COMPLEX MOSAIC IMAGES LASER-ENGRAVED ON WOOD

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ABSTRACT

The results of developing a coloristic series with a greater number of visually distinct color shades for laser engraving complex mosaic images on beech and aspen wood are presented in the paper. Two independent methods used to study the engraved wood shade yielded consistent results: instrumental, based on determining color coordinates in the Lab system, and visual, based on tone expert evaluation. The reduced discretization step of the tone gradient ΔE_s to two E units combined with simultaneous tone gradient spread, allows increasing the number of shades and extending the coloristic series of engraved beech and aspen wood. The successive power elevation caused by the computer template raster (resolution) density growth results in the formation of three distinctive regions on the tone gradient: the light-toned region, the darkened region, and the lightened region. The integrated coloristic index E decreases in the first two regions but increases in the third one due to the light reflection by carbonized wood cells.

Keywords: wood; laser engraving; tone gradient; absorbed power; coloristic series.

INTRODUCTION

Laser engraving is successfully used to produce and decorate items made of wood and other wood-based materials.

The practical application of engraved wood color has been described in several works. Petutschigg *et al.* (2013) got new aesthetic opportunities in ski design. Jurek and Vagnerova, 2021; Gochev and Vitchev, 2022; Zukova *et al.,* 2022 engraved photo replicas on beech wood and birch plywood; Lungu *et al.,* 2022 decorated maple furniture with traditional Romanian ornaments to preserve cultural identity. Chernykh *et al.* (2018) produced a series of decorative panel pictures from the veneers of various wood species. Evdokimova (2023) described the possibilities of improving the quality of pseudo-3D images engraved on birch wood by more fully exploiting its coloristic properties.

Numerous papers have been dedicated to studying the interconnection between the color of laser engraved wood and wooden materials with changed chemical properties, roughness, engraving modes: Hill *et al.,* 2006; Barchikovski *et al.,* 2006; Lin *et al.,* 2008; Kubovsky and Babiak, 2009; Chernykh *et al.,* 2011, 2012, 2015; Kubovsky *et al.,* 2016; Yakimovich *et al.,* 2016, Vidholdova *et al.,* 2017, Gurau *et al.,* 2017; Geffert *et al.,* 2017; Li *et al.,* 2018; Kudela *et al.,* 2019, 2022, 2023.

The accumulated knowledge and practical experience enable the shift from copying existing photographs and images to designing them for further laser engraving. Such approach is based on taking into account coloristic capabilities of the engraved wood and achieving the color match between the carved image and developed drawing in the image (drawing) design (Chernykh *et al.,* 2024).

Such matching allows the customer to select the engraved image color palette at the time of placing an order and even to participate in the creation of the drawing's coloristic solution, thus increasing the chances of selling the item.

Despite selling custom-made items, another group can be singled out: items produced without the customer's participation, following the designer's project, and displayed for sale. To succeed in business, the designer must predict the buyers' perception.

The laser engraved wood has a brown color with various shades, and the image three-dimensionality is achieved by the shade difference – different color saturation. The tone changes smoothly in half-tone drawings and photographs, but in mosaic drawings, widely used in fine and decorative art (Figure 1), it changes discretely, stepwise.

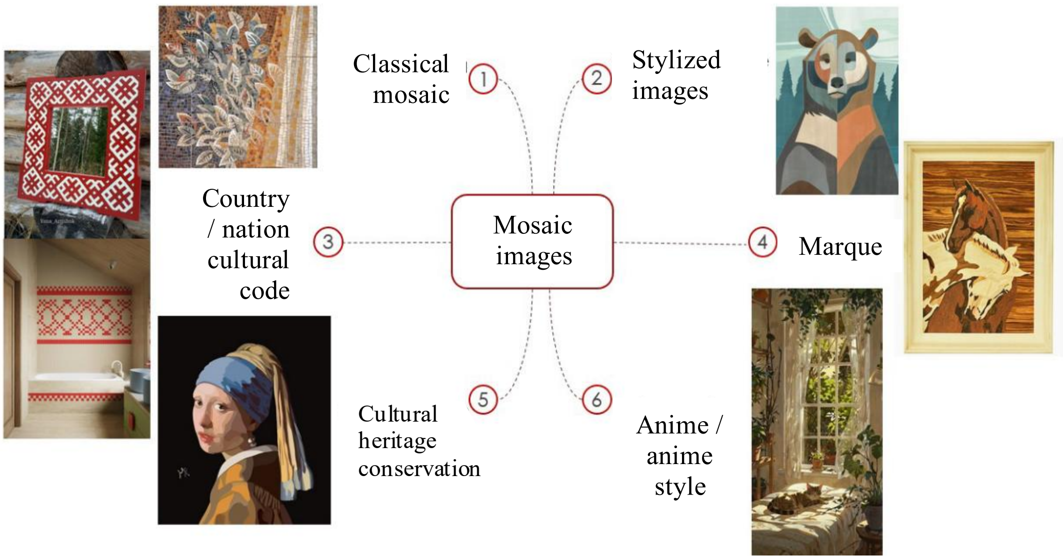


Fig. 1 Areas of mosaic drawing application.

To create a mosaic drawing for further laser engraving, it is necessary to discretize the tone gradient of the laser engraved wood.

The discretization step of the tone gradient ΔE_s is found as

$$\Delta E_s = |E_1 - E_2| \qquad (1)$$

Where: E_1, E_2 – values of integrated coloristic index E of the tone gradient stages compared,

$$\sqrt{L^2 + a^2 + b^2} \qquad (2)$$

Where: L, a, b – color coordinates in Lab system.

In Chernykh *et al.* (2024), the discretization step for the tone gradient of the engraved aspen wood sample was set to 6. With such a value of ΔEs, only six stages can be singled out in the tone gradient of aspen (as well as other wood species discussed in the paper – birch, pine, larch, beech, and spruce).

Six tone shades are not enough to create a complex mosaic drawing; therefore, it is of practical interest to increase their number by reducing the discretization step to the minimum possible.

With more mosaic image shades used, it becomes possible to increase the number of its small elements, making the image more comprehensive and volumetric and thus improving its quality.

The decrease in the discretization step is limited by the tone threshold distinction by the human eye Δ, Ep, at which the visual difference of the color series stages, similar in tone, disappears.

The contrast sensitivity of the human eye has been studied in several works. For this, Antipin (1970) and Mikov and Morozov (2007) compared the brightness of the image background and details.

$$\varepsilon_p = \frac{\Delta B_p}{B} \tag{3}$$

Where: ε_p – contrast sensitivity;

B – mean value of brightness of the compared spots;

ΔB_p– threshold distinction between the brightness of two compared neighboring color spots by a human eye (for example, the image background and details)

$$\Delta B_p = B1 - B2 \tag{4}$$

Where: B1 and B2 – brightness of the compared spots.

Not only brightness but also color tone influences the harmonic perception of the laser-engraved image (Jurek and Vagnerova, 2021); therefore, the integrated coloristic index E was used in this study instead of brightness.

The work is aimed at forming a discrete series of engraved wood tone gradients with an increased number of shades to develop complex mosaic drawings.

MATERIALS AND METHODS

The discretization step of the tone gradient ΔEs was found by an expert evaluation method in Chernykh *et al.* (2013). The laser-engraved samples of aspen and beech wood, measuring 20×20×300 mm, reported in Chernykh *et al.* (2024), were used in the study.

The samples had a tangential section and a longitudinal fiber direction. Before engraving, the surface was planed on a thickness planer.

Samples' moisture: 12%.

The testing strips were engraved on the samples using a grey computer template with the resolution N uniformly increasing from 0 to 255 or from 0 to 100% of black.

Equipment:

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

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

The sample was placed inside the hollow casing (Figure 2) with a rectangular opening (window) whose dimensions matched those of the tone gradient (20×150 mm) engraved on the sample. The scale with resolution N values was made on one of the longitudinal edges of the casing window according to the values of monochromatic computer template used for gradient engraving on the samples, and on the opposite edge – the scale with values of integrated coloristic index E according to the corresponding gradient values on the sample measured with the help of spectrophotometer GretagMacbeth "Eye-One Pro" (Switzerland).

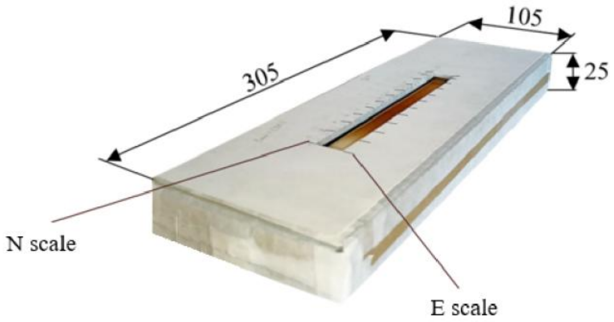


Fig.2 Casing with a fixed sample.

The clearance for placing and moving samples was envisaged between the sample engraved surface and the casing (Figure 3) to observe different regions of the engraved gradient.

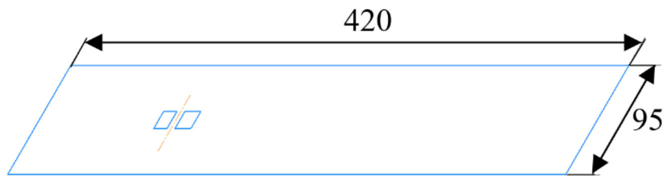


Fig. 3 Sample from white dense paper with windows.

The template window height was 15 mm, and the widths of the first and second templates were 12 mm, and the third was 10 mm. The distances between the middles of the windows were: 18 mm – in the first sample, 13 mm – in the second, and 6.5 mm – in the third, which corresponded to the discretization step of the tone gradient ΔEs equal to 7, 5, and 4 E units.

The experts, moving the templates, compared tone differences across windows and recorded the values of three indices – N and E at the middle of the windows, as well as the presence or absence of a visually perceived tone difference. When available, they put 1 in the "Perception Wi" line of the table, and when unavailable zero.

Tab. 1 Values of measured indices.

Index	Template 1*											
Resolution N, %	5	9	17	24	34	44	53	63	73	82	90	96
Integrated coloristic index E, units	87	86	77	67	62	60	54	52	63	68	71	73
Experts' group perceptionW	0.9	1.0	1.0	0.9	0.9	0.3	0.4	0.9	0.9	0.9	0.9	0.8

*Similar tables were used for templates 2 and 3.

The experts' group collective perception W was found for each selected discretization step based on each expert's individual perception W_i

$$W = \frac{m}{M} \tag{5}$$

Where: m – number of positive replies on the availability of brightness difference between the regions compared;

M – number of respondents (25 designers were interviewed).

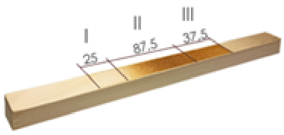
The collective perception W could range from 0 to 1. Its equally probable value was 0.5 when the experts' opinions were similarly divided.

In the paper, we proceeded from the assumption that the collective perception of experts is available and can be compared with the perception of a typical buyer when observing an engraved mosaic image. Suppose most experts can differentiate the tones of the neighboring steps of the coloristic series with a specific ΔEs value. In that case, a typical buyer will also determine the neighboring spots of the image, similar in tone, and understand the designer's drawing based on the coloristic series with the same ΔEs value.

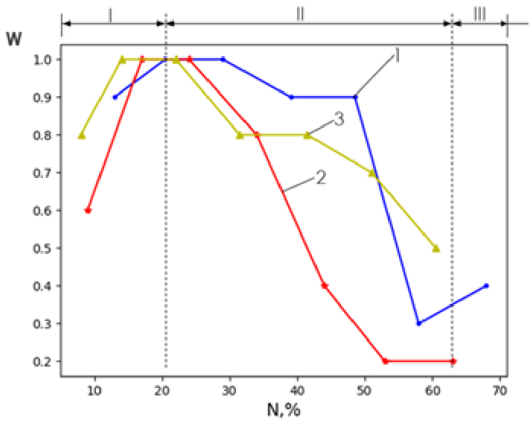
The image, designed based on the research results, was engraved into beech wood using a CO_2 laser engraver, GCC Laser Pro Mercury III (USA), at the maximum power, Pmax = 26 W. The engraving mode: pulse power Pi = 6.5 W, engraving speed V = 1000 mm/sec, laser resolution R = 600 dpi. The beam was focused on the workpiece surface (a focus shift against the engraved surface, both upwards and downwards, increased the line width and blur, thereby deteriorating image quality).

RESULTS AND DISCUSSION

The study results are given in the graphs (Figure 4).



a)



b)

Fig. 4 Engraved tone gradient on the aspen sample (a), dimensions in mm; the graphs of dependence of the experts' groupcollective perception W on the template resolution N with different discretization steps of the tone gradient (b): 1 - ΔE_s = 7 (template 1), 2 - ΔE_s = 5 (template 2), 3 - ΔE_s = 4 (template 3).

Three distinctive regions of the engraved gradient are visually apparent on the sample: I – light-shaded region, II – intensively darkened region, and III – lightened region.

While the template resolution N increased, the number of laser pulses f per unit time, absorbed power PW, and temperature T of the wood heated increased. The surface became darker. In the light shade region, the gradient tone slightly differed from the wood's natural color; the difference was not marked by all experts. Nevertheless, most of them registered surface darkening with increasing resolution N, and consequently, the raster density and absorbed power PW. Perception W in this region exceeded the equally probable value of

0.5, changing from 0.6 to 0.9 depending on the discretization step ΔEs**.** The perception reached its maximum value of 1 near the boundary between regions I and II. The experts' perception in the area I agreed with the results of the previous investigation reported in Chernykh *et al.* (2024): the integrated coloristic index E slightly decreased in region I (Figure 5).

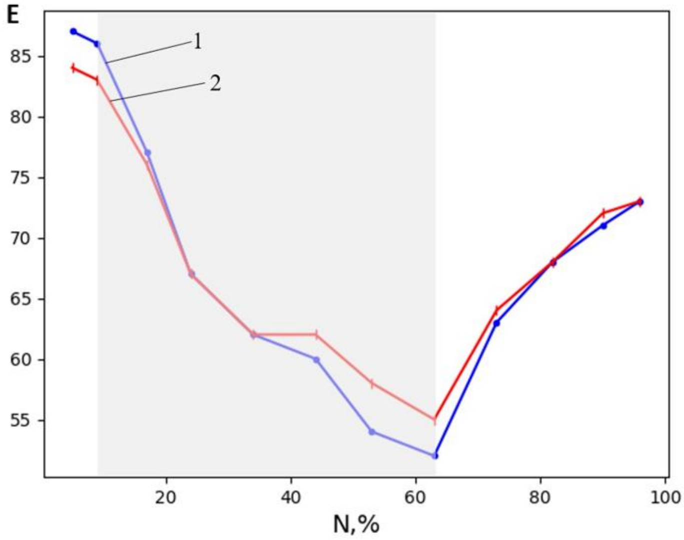


Fig. 5 Dependencies of the integrated coloristic index E of the tone gradient of the sample engraved on aspen upon resolution N according to Chernykh, M. et al. 2024 (1) and printed out on paper (2).

When we continued comparing Figures 4 and 5, we discovered that the integrated coloristic index E was changing most in the beginning of the region II till the resolution N value approximately equal to25-23%, and simultaneously the maximum value of perception W was preserved, registering the intensive tone change.

Further, the decrease in perception W was observed in region II, together with N growth, and, at the same time, the reduction in E values slowed.

W and E values were minimal at the boundary of regions II and III, and the darkest tone was reached when the tone threshold of the engraved wood was reached.

With further resolution N increase and, consequently, the number of laser pulses *f* per time unit, as well as the average laser radiation power Pc, absorbed powerPw and heating temperature T, the sample surface did not darken but, on the contrary, lightened, the integrated coloristic index E started growing, and the perception was the least. Kudela et al. (2023) pointed out that wood color could serve as an indicator of significant changes in its properties resulting from processing. Judging from the graphs of color change demonstrated in Figures 4 and 5, it can be assumed that carbonization of separate wood cells and lightning connected with it started at an early stage of laser processing (in our case, it began when resolution N approximately equaled 25-30% when, simultaneously, E decrease was slowing down, and perception W was decreasing). The assumption was supported by investigation results on the engraved spruce wood microstructure, which demonstrated the simultaneous presence of carbonized and non-carbonized cells (Kudela *et al.,* 2024).

Further, with N growth, the number of carbonized cells and the light-reflection area gradually increased, reaching a level that led to further tone lightening of the overall engraved surface.

The slowing down of lightening L and integrated coloristic index E decrease with the increased laser beam power (and, consequently, radiation dose, as well as absorbed power

Pw) were observed on beech wood (Vidholdova *et al.,* 2017, Kudela *et al.,* 2019), maple wood (Lungu *et al.,* 2022), oak and spruce wood (Kudela *et al.,* 2023, 2024).

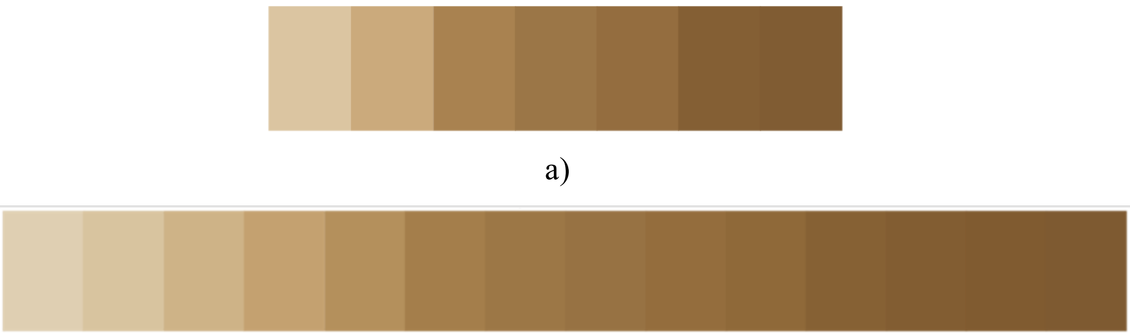
The lightning effect limited the range of E values and the number of coloristic series shades.

On the whole, based on the graphs shown in Figures 4 and 5, it is possible to observe a match between the change characteristics of the integrated coloristic index E and perception W as a function of template resolution N and absorbed power Pw.

The proposed decrease in the tone gradient discretization step to ΔE equal to 4 allowed extending the gradient coloristic series to seven stages, which was insufficient to design a complex drawing.

The study continued with models that allowed transforming the tone change intensity along the gradient length, due to its extension, and thereby obtaining a greater number of stages in its coloristic series.

For this, the sample tone gradient was transferred to paper in the computer program (graph 2 in Figure 5). Some discrepancy in the E values between the sample and the model can be explained by the influence of wood texture. The models' tone gradients were discretized with steps ΔEs = 4 and ΔEs = 2 (Figure 6). The decrease of the discretization step ΔEsto 2 allowed doubling the number of stages of the coloristic series.



a)

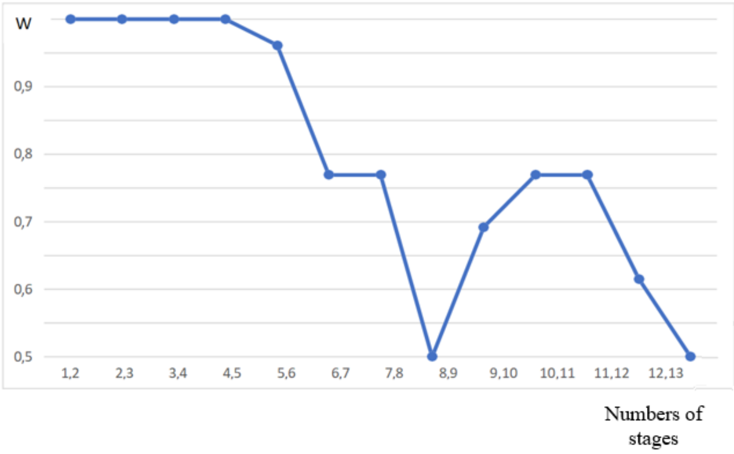
b)

Fig. 6 Coloristic series of aspen wood formed on models with discretization step ΔE_sequal to 4 (a) and 2 (b).

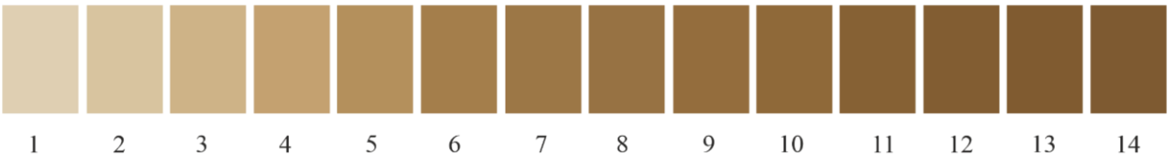
The investigation of perception W of the coloristic series options shown in Figure 6, in which the neighboring stages of the tone shades, directly adjoining each other, demonstrated the influence on the perception of optic illusion called “Mach band” (Ratliff, 1965). The illusion is related to the features of the human visual system and neutralizes the tonal differences between the neighboring stages. As a result, the expert evaluation becomes overrated.

Separation of degrees of coloristic series allowed eliminating the influence of the abovementioned illusion. The graph of perception W of the series with separated stages is given in Figure 7.

(a)



(b)

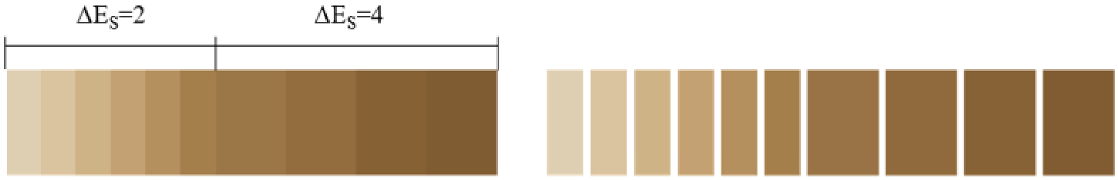


(c)

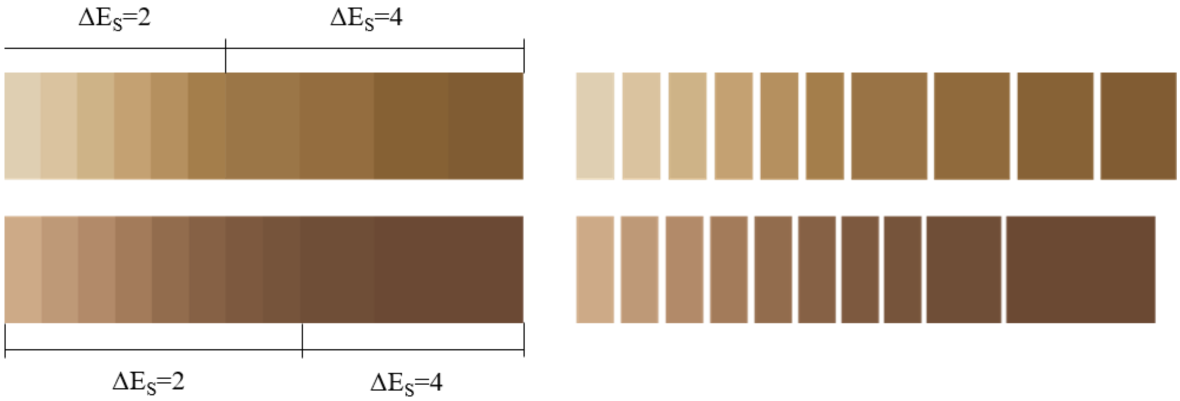
Fig. 7 Texture of the engraved sample in the region II (a), perception of the coloristic series of the aspen wood tone gradient with separated stages with discretization step ΔE_s equal to 2 in the region II, the dots in the graph correspond to the boundaries between the series stages (b); the coloristic series with separated stages (c).

On the whole, the graph in Figure 7 b agrees with the graphs of region II in Figure 4. Thus, the tone changed more in the beginning of region II, and the perception equaled 1; the tone change diminished in the middle portion, the W value decreased, and the perception was minimal in the end. The sharp decrease in perception at the boundary between stages 8 and 9 was influenced by the texture shown in Figure 7a.

Perception W was close to the equally probable value of 0.5 in the area of the tone gradient, in dark shades at the boundaries of stages 6 and 7, 7 and 8, 10 and 11, and 11 and 12. It was necessary to enlarge the discretization step in this area to provide the better perceptibility of the stages, having combined, for example, pairwise, the neighboring stages starting from the seventh for aspen and from the tenth for beech, as demonstrated in Figure 8.



a)



b)

Fig. 8 Specified coloristic series for aspen wood (a); and beech wood (b).

The discrete series with separated stages (Figure 8b, the right one) was used for designing the mosaic drawing.

A bald eagle, considered a holy bird, a symbol of bravery and spiritual bond with the sky by native people of North America, for example, the Navajo, was used as an artistic image for engraving. The drawing contained a lot of mosaic elements of various sizes and shades (Figure 9).

a)

(b)

Fig. 9 Image designed based on the coloristic series given in Figure 8b (a) and laser engraved image on beech wood (b), 130x215 mm.

The computer template for laser engraving was designed based on the drwaing.

CONCLUSION

A method for extending the coloristic series of the tone gradient of laser-engraved wood by decreasing the gradient discretization step and simultaneously spreading tones to provide the opportunity for engraving complex mosaic drawings is proposed. The method allows shifting from copying existing drawings and photographs to their design for further laser engraving, thereby achieving a match of the engraved image color with the designed drawing color.

The investigation of the dependence of the tone change on the absorbed power Pw, carried out by two independent methods – an instrumental method determining color coordinates L, a, b, and an integrated coloristic index E, and a visual method of expert evaluations, demonstrated agreement between the results. The process of expert assessments allows for the identification of consumers' preferences.

While the absorbed power Pw goes up, three distinctive regions are successively formed on the tone gradient of the engraved wood: the region of light tones, the darkened region, and the lightened region. The highest darkening rate is registered at the beginning of the second region; it decreases in descending order in the middle and at the end due to light reflection from the carbonized wood cells. With the absorbed power Pw increasing, the number of carbonized cells and the light-reflection area increase, reaching a level that further lightens the overall engraved surface. The lightened region emerges on the tone gradient. The lightening effect limits the targeted color change opportunities for laser-etched wood within a specific range of E values, particular to each species.

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