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CHANGES OF THE WOOD SURFACE COLOUR INDUCED BY CO_2 LASER AND ITS DURABILITY AFTER THE XENON LAMP EXPOSURE

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ABSTRACT

We have studied colour changes of the wood surface induced by CO_2 laser irradiation and its durability. First, the surface of lime wood (*Tilia vulgaris* L.) was irradiated with the beam of CO_2 laser (wavelength 10.6 μm, power 400 W). When increasing the dose of irradiation (8-29 $J.cm^{-2}$), the brightness uniform decreases (ΔL^*) and the total colour difference (ΔE^*) increases. Changes in chroma (Δa^* and Δb^*) have also been observed. After laser treatment of wood, the same specimens were exposed to radiation of the xenon lamp in the Xenotest chamber. The time of exposition was 100 hours. After this time, the colour values were compared with the values obtained after modifying by CO_2 laser (before UV irradiation). Colour measurement was carried out in both the cases with the spectrophotometer. Results were expressed by colour differences in the CIELAB colour space. The xenon lamp radiation exposure caused quite significant colour changes. The largest increase was recorded in the total colour difference (from 5 to 16), which is considered as very great.

KEYWORDS: Lime wood, laser irradiation, colour changes, irradiation dose, UV radiation.

INTRODUCTION

Lime wood is soft, light and well-machinable. Therefore, it is often used in musical instrument manufacturing and carving. Colour is a very important characteristic of wood usually used in its natural colour as well as after its colour treatment. The traditional process for colour changes is painting (application of coating with a coloured varnish). In addition, the colour of wood can be changed by modifying of wood structure of its main components (cellulose, hemicellulose, and lignin), mainly due to heat, humidity, light or UV radiation. The degradation of wood components will form chromophoric groups of lignin. These structures are responsible for the wood colour changes. Thermally modified wood offers use in outdoor furniture, flooring material, cladding on wooden buildings and in a number of other outdoor and indoor applications (Nuopponen et al. 2004). The thermal treatment may be provided by electric heating, infrared or microwave heating (Bourgois 1989). As an unconventional source of wood surface heating may be used CO_2 power laser although its application area is especially in cutting (Zhou and Mahdavian 2004, Kubovský et al. 2012), drilling, engraving, and marking (Chitu et al. 2003). Laser power for surface treatment can be used for desirable colour changes.

Wood surface is usually exposed to the environment which raises its degradation. Sunlight, heat, and moisture can cause serious deterioration of a wooden product, such as colour change, cracking or loss of strength (Tolvaj and Faix 1995). Great influence upon the change of the colour of wood is given by UV radiation (Müller et al. 2003, Persze and Tolvaj 2012). This component is also included in the sunlight. A result of photooxidative processes in lignin macromolecules induced by UV radiation is the yellowing of some types of wood, its fading and greying. Ultraviolet light causes almost all photodegradation of materials exposed outdoors (Reinprecht and Pánek 2013).

The aim of this work was to investigate the durability of colour created by irradiation with the carbon dioxide laser after exposition to UV radiation by using of the special xenon lamp. Studies have shown that the filtered Xenon lamps are the best method to test a lot of products which may be sensitive to the longer UV wavelengths and visible wavelengths of sunlight (Rosu et al. 2010).

Colour and its interpretation

To quantify the colour we used three dimensional colorimetric system $L^*a^*b^*$ (also known under the name of CIELAB) established by the CIE (International Commission on Illumination) in 1976. This colour space is based on the fact that a colour cannot be simultaneously red and green (or blue and yellow), because these colours are opposite each other. Model of this system (Fig. 1) consists of three mutually perpendicular axes: axis L^* determines the lightness from 0 (black) to 100 (white), axis a^* determines the ratio of red (positive) to green (negative), and axis b^* specifies the ratio of yellow (positive) to blue (negative). Axes a^* and b^* create together the chromaticity plane.

To assess the difference of the two colours there is used total colour difference ΔE^* expressing the distance between two points in the CIELAB system:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{1}$$

where: ΔL^*, Δa^*, Δb^* are differences in individual axes (difference between the value measured after irradiation of the sample and the reference sample). Relationships between objective assessment of colour difference obtained by measurement and visual evaluation of colour differences are shown in Tab. 1.

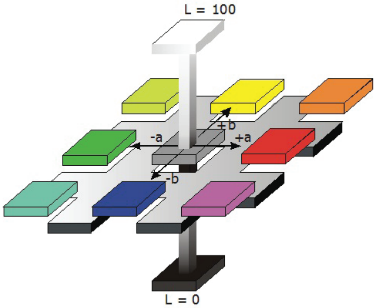

Fig. 1: Model of the CIELAB colour space.

Tab. 1: Comparison of the colour differences obtained by measuring and the visual perception (Katuščák 1994).

The measured *E**	Colour change on the basis of visual assessment
0 – 0.5	negligible
0.5 – 1.5	small
1.5 - 3	noticeable
3 - 6	significant
6 - 12	great
over 12	very great

MATERIAL AND METHODS

Material

Experimental samples of lime wood (*Tilia vulgaris* L.) with the size of 15 x 140 x 500 mm (thickness x width x length), were obtained by the tangential cut from the trunk of the tree. The samples were conditioned to 12 % absolute humidity. Before starting the experiment, the surface was sanded by the glass-paper with No. 150 roughness, deprived of dust and dirt. The colour changes were measured using the spectrophotometric method. Colour values are expressed in the CIELAB colorimetric system.

Irradiation by CO_2 laser

The laser equipment LCS 400 was used for irradiation. This device consists of CO_2 laser (wavelength of 10.6 μm with maximum power output of 400 W), positioning table system (allowed the laser head positioning and raster scan of the laser beam) and the computer control system. The laser beam struck perpendicularly the sample surface and laser head moved along the width (in the direction of the axis *x*) at a certain velocity (Fig. 2). After scanning all width of the sample, the laser head was shifted in the length direction (in the direction of the axis *y*). The velocity increased and the whole process was repeated. On the surface, the parallel system of stripes with different colours (with the hue from light brown to black) was created. Each of these stripes received different irradiation doses H (H varied from 8 to 29 J.cm^{-2}, it corresponds to carriage velocity from 7 to 2 mm.s^{-1}). The effective power of the laser beam was adjusted to 45 W and its width was 8 mm (measured on the surface of the wood specimen).

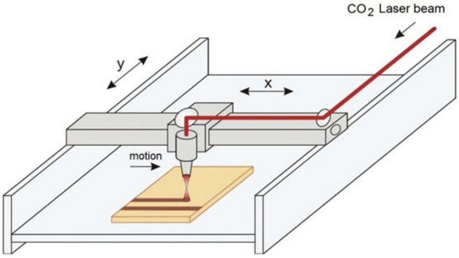

Fig. 2: Scheme of the apparatus for CO2 laser irradiation.

Immediately after creating the whole system of stripes, colour was measured on each of them. Results are presented in Tab. 1. Values are valid for 95 % variability limit.

Measurement of colour

The colour was measured with the portable spectrophotometer CM 2600d (Konica Minolta). The system uses two xenon flashes (one including UV and the other one excluding UV energy). Measurements were made using the SCI (Specular Component Included) lighting system with the D65 light source by simulating the daylight in wavelength range from 360 to 740 nm. The sensor head was 6 mm in diameter. The internal software contains all necessary colorimetric equations. All values of L^*, a^*, and b^* were obtained after each measurement automatically. These data are used to calculate other parameters, such as ΔE^* (according to Eq. 1). To improve properties of the spectrophotometer there is used the "SpectraMagic" software owing to which the process of colour measurement can be easily controlled and all data exported to Excel.

Irradiation in Xenotest

Durability of colour changes induced by CO_2 laser was verified on samples using the method of accelerated aging. For this purpose, the chamber of Xenotest (Q-SUN Xe-1-S Q-Lab Corporation) has served. Due to limited space in the chamber there was a plate with the created stripes divided into ten smaller parts irradiated by the 1800 W xenon lamp (without water). The lamp in Xenotest was surrounded by the light and heat filter to simulate a daylight sensor and UVA-340 (Reinprecht and Pánek 2013). Exposure time was set at 100 hours with the irradiance value of 0.55 W.m^{-2} (black panel with temperature 50°C, Daylight filter Q-X-7460). The lamp in Xenotest reproduces the damaging wavelengths of light encountered either indoors or outdoors. This source emits ultraviolet, visible and infrared light.

The colour was measured on the surface of the exposed samples again to calculate differences before and after irradiation in the chamber. Colour differences were calculated using the following formulas:

$$\Delta L^* = L^*_{Xe} - L^*_{CO2} \quad (2)$$

$$\Delta a^* = a^*_{Xe} - a^*_{CO2} \quad (3)$$

$$\Delta b^* = b^*_{Xe} - b^*_{CO2} \quad (4)$$

where: the values with the "CO_2" suffix represent the colour of the stripes obtained after laser irradiation (before treatment in Xenotest) and the values with the "X" suffix are valid for the same stripes on the specimen with subsequent irradiation in Xenotest. The total colour difference ΔE^* was calculated according to the Eq. 1.

RESULTS AND DISCUSSION

The measured and calculated results are presented in the following tables. The values are valid for 95 % variability limit.

Colour values after CO_2 laser created stripes

The values of colours for each stripes are given in Tab. 2. The area marked as "LREF" was not irradiated (native wood). The photo of the samples obtained after CO_2 laser modification is depicted in Fig. 3.

Tab. 2: Measured values of L^*, a^*, b^* after CO_2 laser irradiation.

Stripe	LREF	L71	L68	L65	L62	L59	L56	L53	L50	L47	L44	L41	L38	L35	L32	L29	L26	L23	L20
H ($J.cm^{-2}$)	0	8.1	8.4	8.8	9.2	9.7	10.2	10.8	11.5	12.2	13.0	14.0	15.1	16.4	17.9	19.8	22.0	24.9	28.7
L^*CO_2	78.48	70.67	70.97	69.07	67.90	68.97	69.89	68.83	66.90	67.30	63.37	61.19	53.91	49.96	45.87	40.85	35.17	28.11	27.98
a^*CO_2	6.43	8.94	8.71	9.09	9.25	9.03	8.65	8.93	9.90	9.43	9.56	10.19	10.89	10.45	10.31	9.39	7.42	3.79	2.34
b^*CO_2	26.25	27.47	27.31	27.13	26.90	26.45	25.81	25.75	25.88	25.70	25.83	24.57	22.41	21.45	21.09	17.47	13.02	5.83	3.50

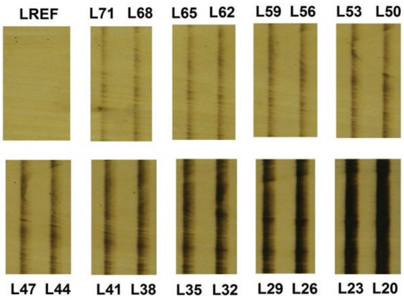

Fig. 3: Lime wood surface irradiated by CO_2 laser.

1. The results obtained in measuring the colour show that the increase in the irradiation dose (*H*) causes changes in the values of all variables in the CIELAB system (Tab. 2). With increasing *H* from 8.1 to 28.7 $J.cm^{-2}$, we observed a continual decrease of L^* from 71 to 28. L^* decreased slightly to the value of the irradiation dose of 11 $J.cm^{-2}$, then continuously decreased to the value 25 $J.cm^{-2}$. Over the value 25 $J.cm^{-2}$, we observed blackening of wood ($L^* < 28$).
2. The value of a^* varied from 8.9 to 10.9 up to $H = 11$ $J.cm^{-2}$, when it started increasing (with its maximum $a^* = 10.9$ at 15.1 $J.cm^{-2}$). Then it steadily decreased up to the value of 2.3 (reduction of red component). After the initial slight increase, the value of b^* steadily declined. Over 20 $J.cm^{-2}$, this value began to decline sharply until it stopped at the value of 3.5. The trends of the observed colorimetric values a^* and b^* show that the increasing of the irradiation dose moves the colour to the brown hue.

Colour values after exposition in Xenotest

The durability of colours achieved by laser in relation to artificial sunlight was assessed on the basis of the colour differences on the samples after exposing in Xenotest. The measured values are listed in Tab. 3. The photo of the samples obtained after exposition in Xenotest is illustrated in Fig. 4.

Tab. 3: Measured values of L^*_{Xe}, a^*_{Xe}, b^*_{Xe} *after the exposition in Xenotest.*

Stripe	LREF Xe	L71 Xe	L68 Xe	L65 Xe	L62 Xe	L59 Xe	L56 Xe	L53 Xe	L50 Xe	L47 Xe	L44 Xe	L41 Xe	L38 Xe	L35 Xe	L32 Xe	L29 Xe	L26 Xe	L23 Xe	L20 Xe
L^*_{Xe}	76.87	75.2	75.07	75.11	74.21	74.14	74.52	74.35	72.85	71.92	70.85	71.23	65.7	62.11	57.42	55.1	49.85	38.84	35.23
a^*_{Xe}	6.8	6.99	7.02	7.06	7.29	7.19	7.23	7.42	8.03	8.2	8.27	7.82	9.16	8.71	8.32	7.79	7.6	5.61	4.4
b^*_{Xe}	27.26	27.35	27.25	27.08	27.18	26.96	27.25	26.97	27.76	28.38	27.43	26.06	25.81	24.03	21.33	20.21	18.6	12.83	9.22

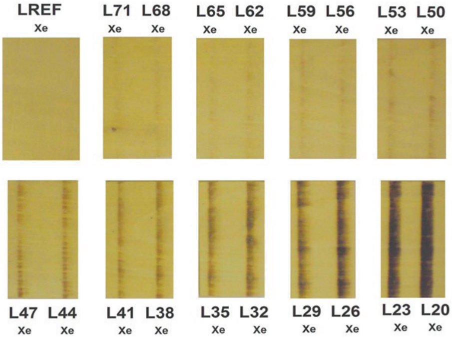

Fig. 4: Lime wood surface after irradiation by the xenon lamp.

After irradiation in Xenotest, *L** was increased on all stripes. An exception is the reference sample, whose surface has darkened. The *a** value significantly decreased in all samples (except of stripes with the highest dose of irradiation). The *b** value increased gradually, however, initially only very slightly. Over the value of 12 J.cm^{-2} (stripes from L47 to L20), the increase was more noticeable.

Colour differences

Calculated colour differences on the stripes created by laser before and after the irradiation by the xenon lamp are listed in Tab. 4 and illustrated in Fig. 5.

Tab. 4: Calculated values of ΔL^*, Δa^*, Δb^*, *and* ΔE^* *after the exposition in Xenotest.*

Stripe	LREF Xe	L71 Xe	L68 Xe	L65 Xe	L62 Xe	L59 Xe	L56 Xe	L53 Xe	L50 Xe	L47 Xe	L44 Xe	L41 Xe	L38 Xe	L35 Xe	L32 Xe	L29 Xe	L26 Xe	L23 Xe	L20 Xe
ΔL^*	-1.45	4.53	4.10	6.04	6.31	5.17	4.63	5.52	5.95	4.62	7.48	10.04	11.79	12.15	11.55	14.25	14.68	10.73	7.25
Δa^*	0.26	-1.95	-1.69	-2.03	-1.96	-1.84	-1.42	-1.51	-1.87	-1.23	-1.29	-2.37	-1.73	-1.74	-1.99	-1.60	0.18	1.82	2.06
Δb^*	1.98	-0.12	-0.06	-0.05	0.28	0.51	1.44	1.22	1.88	2.68	1.60	1.49	3.40	2.58	0.24	2.74	5.58	7.00	5.72
ΔE^*	2.35	4.93	4.44	6.37	6.61	5.51	5.05	5.85	6.51	5.48	7.76	10.43	12.39	12.54	11.72	14.60	15.70	12.93	9.46

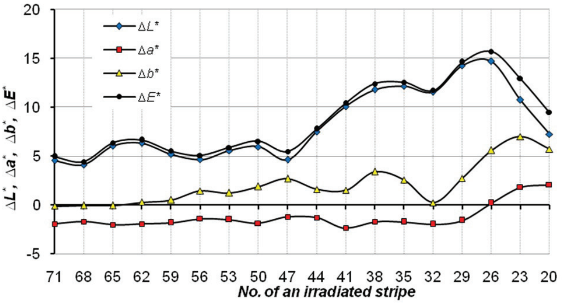

Fig. 5: Colour differences of lime wood stripes after the exposure in Xenotest.

According to the values given in Tab. 4, we observed darkening of the surface (ΔL^{*}= -1.4) on the reference sample. For all the stripes, ΔL^{*} increased, which was indicated by a slight fading of wood surface. On the stripes (L71-L41) irradiated with the dose of the CO_2 laser below 14 J.cm^{-2}, ΔL* does not exceed the value of 10. Top fading ($\Delta L^{*} > 14$) was manifested on the stripes (L38-L26) irradiated with higher doses (H from 19 to 25 J.cm^{-2}). At H values over 25 J.cm^{2}, ΔL^{*} returned below 10. At the same time we observed a shift to the shades of grey. Similar results were obtained by other authors (Oltean et al. 2008).

The colour difference Δa^{*} showed only minimal changes in all investigated samples (from -2.4 to 2). The change of Δb^{*} was more significant (stripes irradiated by over 22 J.cm^{-2} amounted Δb^{*} circa 7). Positive colour difference Δb^{*} means moving to a yellow colour (which is also visually confirmed). The total colour difference ΔE^{*} practically coincides with the value of the lightness difference ΔL^{*} (because Δa^{*} and Δb^{*} have only a little impact on the final result).

CONCLUSIONS

The aim of these experiments was to verify a colour stability and its durability after UV light exposition. The results show that the durability of colour changes achieved by CO_2 laser and exposed to simulate sunlight is not too high, because we observed quite significant colour changes. To confirm the obtained results it is necessary to carry out further experiments with other wood species. In order to ensure a long-term durability of colours it is needed (especially when used outdoors) to protect the wood with a special UV resistant varnish.

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