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COLOUR INFUENCE OF THE LASER RASTER SPEED ON WOOD PYROGRAPHY

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Abstract:
*The paper presents the results of experimental research performed on sycamore maple wood (Acer pseudoplatanus L.), burned by a CO_2 laser. The influence of speed and lightness for CO_2 laser burning of sycamore maple wood have been determined. In order to evaluate the colour modifications, which may occur, the samples were treated at different speeds, the other work parameters were kept constant. To evaluate the aesthetic changes, CIEL*a*b* colour measurements were applied. Results showed that the lightness varies from 0.7 to 55.6. The interval limits of speed variation were defined from 75 to 500mm/s. Moreover, main observed effects near to interval limits are discussed. The wood had serious degradation, which increased lightness, at speeds under 75mm/s. No major lightness differences were observed at speeds near 500mm/s. The regression equation was defined. It was shown that the lightness depends on laser speed. Increasing the burning speed increased the lightness, too. The overall conclusion of this research is that the feed rate influences the lightness, but into limited intervals. These findings will be useful to be included in computerized databases for the automatic implementation of laser processes. An application of this study would be into the manufacturing of furniture and other products.*

Key words: *pyrography; wood burning; laser technology; colour; feed rate.*

INTRODUCTION

The colour is an important aesthetic characteristic of wood. Considering that, in our daily life, many objects are made from wood and they have purpose to increase our comfort. Pyrography is a method of increasing aesthetic properties, in the wood industry, by burning in a controlled manner. An attractive design increases sales and consumer satisfaction. Dyeing methods are usually adopted for traditional plain decoration, but these methods can initiate problems, such as chemical pollution and material coverage. Alternatively, laser pyrography can directly mark images on the wood, keeping the natural material texture and colour. The colour change of wood by pyrography is mainly due to changes in its chemical composition. The wood colour will become darker, if it is treated at high temperature. Thus, without any addition of chemical substances (as in the case of coatings), the aesthetical value of wood is increased. Petutschnigg et al. (2013) has used laser technology to increase the aesthetic value of skis.

Leone et al. (2008) observed that lasers are widely used in cutting and welding operations. Kincade and Anderson (2008) estimated that more than 40,000 cutting machines using CO2 lasers have been installed worldwide. Unlike other plain decorating techniques, pyrography has some advantages, for example: it is an inexpensive technique, ecological, and available. Several advantages of using CO2 laser irradiation on wood were observed by Kacík and Kubovsky (2011). In contrast to conventional colouration methods, lasers can change colour (from natural wood colour to black) only by delivering energy in the form of electromagnetic radiation.

The speed of the head along the X axis, named as the feed rate, is one of the important parameters in the engraving process because it influences the productivity. Theoretically, the feed rate can vary considerably, from 0mm/s to supersonic values. A speed of 0mm/s is not used for engraving because the processed surface is very small. A surface given by the diameter of the laser spot is difficult to observe with the eyes. On the other hand, the operating principle of the equipment in raster, involves the movement of the working head at a speed no matter how small, but greater than 0mm/s.

In practical terms, this range is limited by several factors:

- Technological possibilities – processing equipment;
- Processing possibilities – the physical phenomena that influences the processing;
- Productivity – Getting the desired effect in the shortest time.

Hernández-Castañeda et al. (2011) studied the influence that working laser parameters have on surface colour. They found that the traverse speed is the third most influential factor in the multiple-pass laser cutting process of pine wood. It is directly related to the interaction time between the laser beam and the material, which increases or reduces the irradiance of energy in the cut process, especially when this factor interacts with laser power.

The feed rate influences the quality of the process. Processing is better at low speeds. At high feed speeds, the wood surface is improperly processed due to insufficient irradiation time. In view of the above, it is clear that the choice of feed rate is a real challenge, or the choice of working regime, because high speed increases productivity, but quality decreases, and low speed produces good quality but low yield. In their study of the influence of working parameters on quality laser processing, working for cutting stainless steel by pulsed Nd:YAG laser, Ghany and Newishy (2005) showed that the laser cutting quality depends mainly on the cutting speed, cutting mode, laser power and pulse frequency and focus position. Riveiro et al. (2010) performed cutting tests in pulsed mode. They demonstrated that the application of laser cutting techniques to process an aluminium–copper alloy can give a good-quality result, with adequate cutting rates. Also, Riveiro et al. (2010) indicated that high cutting speed and good quality can be obtained using high laser powers and focusing the laser beam onto the surface of the workpiece.

Comparing with the cut, the burning grade can be associated with the heat affected zone (HAZ) effect. Hamoudi (1997) showed that, during cutting by a 2 kW CO_2 laser assisted by 10 bar of nitrogen, increasing the cutting speed leads to narrow HAZ. Biermann et al. (1991) and Stournaras et al. (2009) have done some experimental work to explore the influence of HAZ parameters on the cut quality.

Usually pyrography is made on wood, but Irish (2012) proposed more materials used for pyrography, for example: leather, gourds, cloth, and paper. Researchers from the University of Warwick proposed MDF as a support material for laser pyrography (Howard 2014). The global trend in the use of lasers for fast growing wood species was observed by Petutschnigg et al. (2013).

OBJECTIVE

The aim of this work is to study the influence of feed speed on the darkening of the surface of sycamore wood. It has evaluated the colour in terms of luminance, or lightness, a component of the CIEL*a*b* system. The study proposed to obtain the variation law and range limits of the feed speed depending on lightness, without greater degradation of wood.

MATERIAL, METHOD, AND EQUIPMENT

The base material used in this study was sycamore maple (*Acer pseudoplatanus* L.) solid wood. The mechanical properties of this material are listed in Table 1. Cismaru and Cismaru (2007) recommend this species in the wood industry as: piano, violin and double bass parts; parquet and panelling; aesthetic veneers; chairs, table tops; and Filipovici (1965) appends to this list: turned and milled objects. This species is one of the most used species, recommended as a support for pyrography (Filipovici 1965, Bucur 1978, Walters 2005, Neill 2005, Easton 2010, Millis 2013, Gregory 2014). Sycamore maple is an important wooden material used in industry. Thanks to its aesthetic properties (colour and texture), it is suitable to be pyrographed by laser. Meier (2017) describes sycamore lumber as sapwood colour ranging from almost white, to a light golden or reddish brown, while the heartwood is a darker reddish brown. The white colour provides the possibility of obtaining a large colour gradient after burning. Grain is generally straight, but may be wavy. It has a fine, even texture. This texture provides the possibility to create a wide range of pyrographed patterns. Stanciu et al. (2015) observed that sycamore is spread all over the mountain and piedmont of the Carpathian area and in economic terms, the price of sycamore logs at timber auctions in Europe is somewhere around € 640/m^3 at the time of writing. Sycamore wood is much appreciated. Antonoaie et al. (2015), discussing the Brasov - Covasna area, showed that if there is at least 5% sycamore in the total wood volume, this is one of the factors that would persuade a manager to bid to a selling price 40% higher than the asking price at auction.

The wooden material used in the present research consisted of 235×85×10mm boards. In order to analyse the colour of wood, the tangential surface of samples was used. The work surface was chosen to contain mature and juvenile wood strips. The specimen boards were dried at 12% moisture content and conditioned at 20ºC temperature and 65% relative humidity as considered by Cismaru (2003). Before laser processing, the wood specimens were sanded with 80 grit sand paper and then sanded with 120 grit sand paper.

The equipment used was: Laser Engraving Machine 4030lsct, HP LaserJet 3055 all-in-one multifunctional printer for image scanning, PC for image processing, measurement and data analysis.

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Table 1

Physical and mechanical properties of Sycamore Maple (Acer pseudoplatanus L.), according to Meier (2017)

Average Dried Weight	615 kg/m^3
Specific Gravity (Basic, 12% MC)	0.48, 0.62
Janka Hardness	4,680 N
Modulus of Rupture	98.1 MPa
Elastic Modulus	9.92 GPa
Crushing Strength	55.0 MPa
Shrinkage	Radial: 4.5%, Tangential: 7.8%, Volumetric: 12.3%, T/R Ratio: 1.7

Because the literature does not provide clear information in this way, it is necessary to study a wide range of speed variation, from 500 to 0mm/s. The experiments were performed with a 40W CO_2 slab laser. In order to study the variation in feed rate for 16.5W laser power, 20 experiments were designed. Feed rate variation ranged from 25 to 500mm/s, with steps of 25mm/s between experiments. Of these, 19 experiments were made because at the feed rate of 50mm/s the wood ignited. This phenomenon is not acceptable for pyrography. For this reason, no experiments were performed at values lower than this feed rate. The other operating parameters were kept constant. The experiments conducted in pulsed mode were performed varying one parameter (just feed rate). The ranges of engraving parameters are summarized in Table 2. For each working regime a square surface measuring 20mm was processed. In order to compare the results, the experiments were performed in the direction of the wood grain.

Table 2

The range of variation of the engraving parameters

Processing parameter	**Value**
Laser power (W)	16.5
Feed rate (mm/s)	50 … 500
Pulse frequency (Hz)	20000
Scanning gap (mm)	0.0254
Focal length (mm)	73
Focus position	Surface
Assist gas	Compressed air
Nozzle diameter (mm)	5
Stand-off (mm)	30

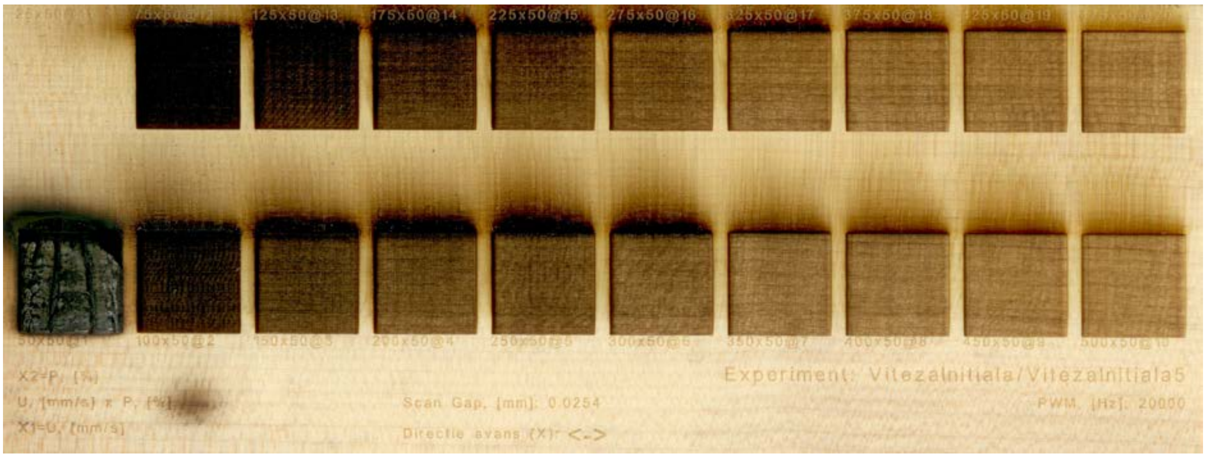

Fig. 1.
Colour scale produced of sycamore showing the effect of speed on wood colour.

The experimental plan was transposed into the machine program using a specialized laser equipment program. The equipment had been adjusted before work was started. A resulting sample is shown in Fig. 1. As can be seen, the arrangement of the experiments was achieved in two rows parallel to the wood grain. Using this arrangement, a number of errors relating to the inhomogeneity of the wood, such as: the annual ring width, the proportion of late and early wood, etc., have been avoided. Drawbacks relating to material preparation such as the cutting direction, fibre direction, etc., have been avoided, as well. Mainly, all these influence the colour of the wood surface. Between processed surfaces, unprocessed areas were also left in order to have the reference surfaces as close as possible to the processed ones.

In order to measure colour, the processed samples were scanned with an HP LaserJet 3055 all-in-one scanner. The selected parameters for this study were:

- Resolution: 600 dpi;
- File format: bitmap;
- Colour mode;
- Scan scale 1:1.

These were set in order to analyse the scanned image file that was transferred to a computer.

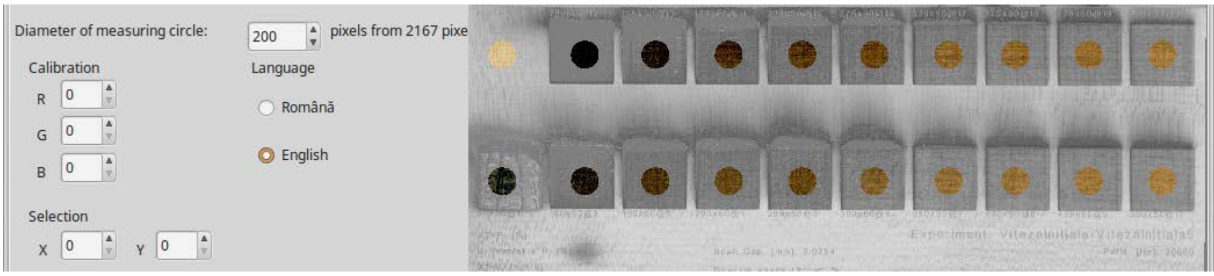

Fig. 2.
The template with measuring points.

The colour was measured using the method presented by Petru and Lunguleasa (2014). Inside of each filled square, the colour was measured at 200 pixels diameter for a circular surface. It resulted in 31587 pixels for each square and 631771 measured pixels for the whole experiment. To simplify all measurements, an electronic template was made using all the measured pixels. Each area, reference and pyrographed, was measured using this template (Fig. 2). To evaluate the colour changes, CIEL*a*b* (1976) colour measurements were applied. This measurement system consists of three coordinates, named: *L**, *a**, and *b**. The *L** coordinate represents lightness and it is on a scale of 100, where L*=100 is white and L*=0 is black. The *a** coordinate characterises the green (negative values), and red (positive values). The *b** coordinate characterises the blue (negative values), and yellow (positive values). This method was preferred because it expresses the colour directly through the lightness parameter, which represents the degree of darkness of the processed surface, respectively the degree of processing. For each measured round area, the average value was calculated for each colour coordinate. The differences between these values, its dispersions and colour change were calculated by using equations (1). The minimum and maximum values were also found.

The colour change was calculated for each colour coordinate (*L*, a** and *b**) as related to its reference area and each processed area. Colour differences between the reference and processed surfaces were calculated by using the following equation as defined in (BS EN ISO 105-J03:1997):

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

where:

$$\Delta L^* = L^*_P - L^*_R$$

$$\Delta a^* = a^*_P - a^*_R$$

$$\Delta b^* = b^*_P - b^*_R$$

P= Pyrographed sample
R= Reference sample

The measured values were recorded and for each speed the average, minimum, maximum, the most often encountered, deviation and standard deviation of colour were calculated. The regression equation was determined.

RESULTS AND DISCUSSION

The trichromatic colour parameter variations, measured in the CIEL*a*b* system, are shown in Fig. 3. The variations of the three colour components are different:

- The *L** parameter, which represents the lightness, has the highest variation and increases proportionally to the increase in the feed rate;
- The *a** parameter, which represents the green colour for negative values and red colour for positive values, has the smallest variation of the trichromatic parameters. Note that this parameter has a negative value at the feed rate of 50mm/s, but at this rate the sample ignited, therefore the result is not included in the present study;
- The b* parameter, which represents the blue colour for negative values and yellow colour for positive values, has a variation smaller than the L* and greater than the a* parameter but closer to the latter. The variation of this parameter can be divided into two distinct areas:
    - At speeds less than 225mm/s, where the values are below the reference value;
    - At speeds greater than 225mm/s, where the values are above the reference value.

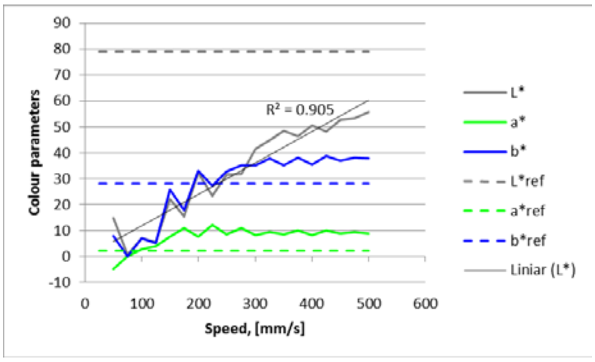

Fig. 3
Average colour variations based on head speed.

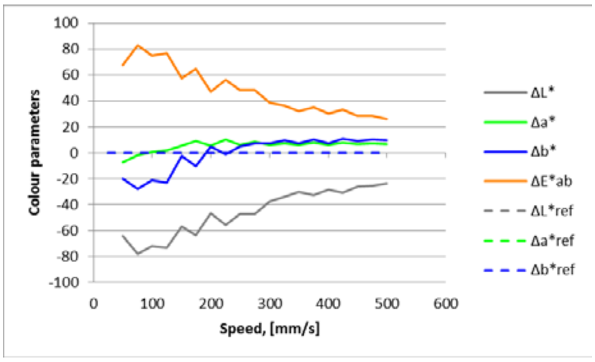

Fig. 4
Colour changes depending on speed variation.
(Please note that the reference samples are all set at zero)

The trichromatic colour differences between the reference surface and the processed surfaces, measured in the CIEL*a*b* system, are shown in Fig. 4. As can be observed, the most influential component, which affected colour difference ΔE_{ab}* is *ΔL**, it has the greatest variation and the curves of these two parameters are similar. *ΔL** varies directly with the increase in speed, respectively, if the feed rate increases, the surface will be lighter. The other two components, *Δa** and *Δb** have a small influence on colour change, compared to the *ΔL**. By comparing treated/processed to reference areas, the first thing one can notice is that the treated areas display the tendency of getting darker (negative values of Δ*L**). Therefore it can be concluded that the simplified analysis of differences in colour nuances need only consider the *L** factor. The darkening tendency of the laser pyrographed samples is stronger during speeds of under 250mm/s.

At first glance, the variance trend of the *L** parameter seems to be linear. The R^2 factor is 0.905. It means that the trend accuracy is very good for an inhomogeneous material such as wood. The tendency is mathematically correct, but physically it is incorrect because, as shown above, processing at the very low feed head speed (0mm/s) is no longer possible, and at very high speeds the wood surface does not change its color because the irradiation time is insufficient to transfer enough energy to the wood surface.

Also in Fig. 3 it can be noticed that there are insignificant changes in colour at high feed speeds. These differences are highlighted by comparing the colour with that of the reference surface. The reference lightness is not equal to 100 because the natural colour of the wood is neither white or uniform. At feed speeds lower than 150mm/s a decrease in lightness is observed. This decrease cannot be continuous because the speed cannot be 0mm/s. It is advisable to avoid low speeds for the following reasons:

- Low productivity;
- Low speed causes heating and attrition of the head moving mechanism;
- Studying the effect of speed and processing gas on laser cutting of steel using a 2kW CO_2 laser, Hamoudi (1997) observed that little dross formed at low speeds of less than than 1m/min and the best cutting quality was achieved at 2m/min. In the case of wood this phenomenon does not carbonise the inorganic components, which increases the surface lightness.

In Fig. 3 it can be noticed that the variation of the *L** component has three distinct intervals of variation:

1. At feed rate values of 50mm/s or less, the wood is burning. The results obtained in these cases were excluded from this study.
2. At an advanced speed of less than 125mm/s, the lightness is almost constant. Working modes with lower speeds than this value are not recommended because there is no greater blackening of the surface. Using speeds in this range generates an unjustified increase in working time.
3. At an advanced speed of higher than 125mm/s the lightness increases. Variations of lightness can be likened to an exponential variation. This is the speed range to be considered further.

Also, in Fig. 3 it is observed that the lightness at high speed (with the minimum surface energy), of 500mm/s, is quite far from the natural colour of the wood. For that it is recommended to use powers less than 16.5W. On the other hand, in Fig. 3 it is shown that the lightness at low speed (maximum surface energy), at feed rates around 75mm/s, is 0.74. This value is quite near to a black colour (the lightness of 0). In the same figure, it is shown that the lightness at high speed (minimum surface energy), at feed rates around 500mm/s, is 55.59. This value is quite far from the reference colour (the lightness for natural wood colour), which is 78.97. It is recommended to use powers lower than 16.5W.

When investigating CO_2 laser cutting of 2024-T3 alloy, Riveiro et al. (2010) following a mathematical modeling, observed that the size of the heat-affected zone at cutting (that is similar to the blackening of pyrography) is influenced by the cutting speed. They believe that this is probably a consequence of the energy released in each processing condition. Modelling the colour lightness variation according to the shape of the exponential function is preferable, because its boundary limits the range of the speed function by setting the upper limit of the speed variation of the laser head, which influences the colour of the treated wood. Considering the above, namely defining an equation that would accurately express the physical phenomena of changing the colour of wood by varying the speed of the laser head, it was proposed to analyse the experimental data. This experimental data was analysed after a predefined function. The trend of lightness variation is exponential. The law of variation is given by the equation:

$$L^*(u) = 73.67 - 95.02\ e^{(-u/295.81)} \qquad (2)$$

where:

- *e* is the basis of the natural logarithm (Euler's number);
- *u* represents the feed rate, in mm/s;
- *L** represents the lightness;

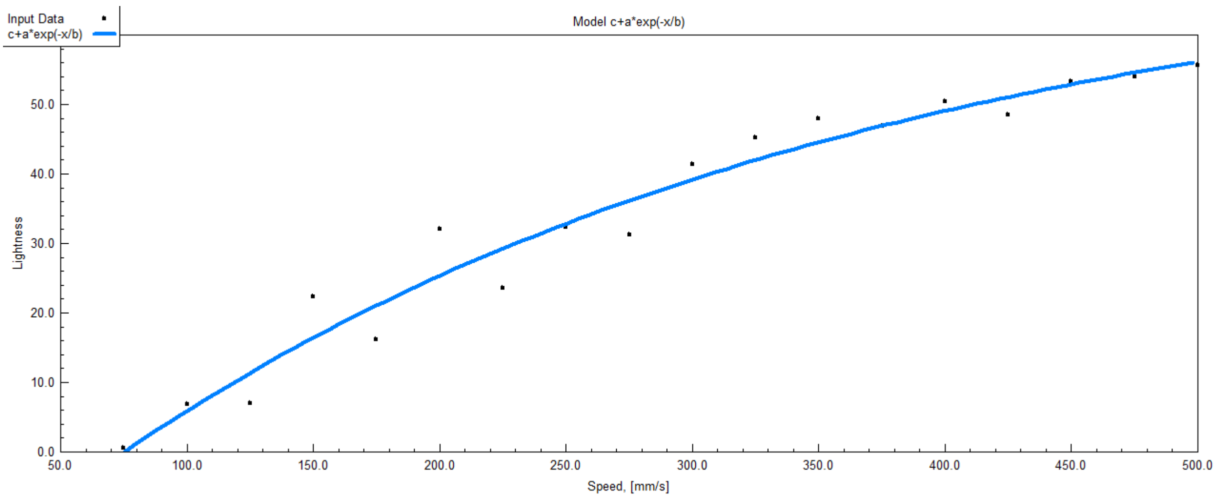

Fig. 5
Lightness variation curve according to speed.

Coefficient of Multiple Determination (R^2) is 0.96, which means that the approximation of experimental results with this variation law is very good, especially for a non-homogeneous material such as wood. The lightness variation curve was designed using equation (2). The lightness variation curve according to speed is shown in Fig. 5.

CONCLUSIONS

The obtained results within the present research demonstrated that the speed has an important influence on wood colouration by laser, even when the other parameters are kept constant. Both early and late sycamore wood have a good colouration using this technology. However, the variation range is limited by physics phenomena happening during laser processing.

Three lightness variation ranges corresponding to the feed rate were identified and defined. Of these, only one interval fulfils the necessary conditions to obtain different luminances used in pyrography. This range from 75 to 475mm/s was defined.

This study confirms the theoretical suppositions, which considers that the lightness variation corresponding to the feed rate is exponential, because processing at the very low end of the feed head speed (0mm/s) is no longer possible, and at high speeds the wood surface does not change its colour because the irradiation time is insufficient to transfer its energy to the wood surface.

At speeds less than 75mm/s there is a large amount of degradation of the material, which shows an increase in lightness. This means that obtained lightness at speeds less than 75mm/s can also be obtained at higher speeds. From this observation it follows that the use of feed rates of less than 75mm/s is not recommended because it is not productive.

The determination of the maximum feed speed is conditioned by the possibilities of the machining of the equipment as well as by the experimental observations that at higher speeds there is no significant change of colour. At feed rates higher than 475mm/s an increase in lightness is noted. This increase is due to the insufficient irradiation time, and the processing cannot be achieved. The same effect can be obtained by using lower laser power. Due to shortcomings in low productivity at low speeds, it is recommended that the variation of the other factors are also studied. Considering the differences between the wood species, the results obtained are valid only for sycamore wood. The method of work can also form the basis of research for other woody species.

Lightness regression equation has been defined according to the feed rate for the studied power. Using this equation, the lightness can also be determined for other working parameters. The laser equipment has been chosen correctly because the range of variation is within the processing possibilities. A detailed analysis of the influence of laser feed rate on the wood was made. The structure of the support material may influence the processing, therefore, the average mean deviation of the measured values has been determined for each measured surface.

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