INVESTIGATION OF THE EFFECT OF LASER RADIATION ON THE MORPHOLOGY AND COLOUR OF BIRCH PLYWOOD

Ginevičienė G., Gudaitienė R., Kujalavičius Ž., Lukaševičiūtė D., Pocienė A.
Kaunas University of Applied Sciences

Abstract
CO_2 laser is commonly used for the production of the advertising material onto plywood, yet the final result of the product depends on the appropriate selection of material, its morphological properties, and technological parameters of material processing. As a result, the change in colour, the depth of the burnt plywood surface due to laser exposure and surface morphology is different. The paper presents the results obtained when the birch plywood is exposed to the CO_2 laser, which renders a specific colour change. The paper also discusses how morphological and roughness parameters influence the colour changes and which material processing mode is the best to achieve a desirable result.
Keywords: *engraving, gas CO_2 laser, glued plywood (fibreboard, birch plywood), ΔE colour change, surface morphology, ablation, carbonisation*

Introduction

In the course of the production of visual products, when a number of various finishing modes are commonly used, the final result of the product depends on the colour change ΔE and morphological properties of the material used. Therefore, it is very important to identify a link between these aspects and the technological parameters that affect them. To process plywood used for the advertising products, gas CO_2 laser is commonly used. The principle of laser beam operation is based on the effect of the concentrated laser beam, which destroys the surface structure of the material. With the help of these devices, computer-generated shapes are transferred onto materials with various morphological and colorimetric properties of the surface. Taking into consideration the selected parameters of laser operation mode, such as the intensity of laser beam and type of the material, different tones of colour of the drawn objects can be obtained (Varanavičienė et al., 2017).

Change in colour can be affected both by the type of wood, laser power, speed of movement, thickness of the material and energy flow density (Petru et al., 2014). Carbonisation process occurs when wood is engraved using a laser. The depth of carbonised wood corresponds to the width of fibre (Dogaru, 1985, cited from Petru et al., 2014). As a result, different intensities of ash colour and brownish colour tones are obtained on the burnt wood surface (Kuktaitė et al., 2020a). Differences in the colour tone of graphic images are obtained as the surface of the material is exposed to different laser power and its movement speed. The colour changes become more pronounced as the speed of laser beam movement decreases, accordingly. An increase in moisture content reduces the effect of carbonisation, as the excess of energy is used for the vaporisation process from wood (Petru et al, 2014). It was observed that the sharpest contrast is obtained when alder, birch and maple plywood is exposed to laser beam radiation.

Plywood is widely used to transfer visual and textual advertising information. Plywood is environmentally friendly, easy to recycle and cost-effective material suitable for the production of products where laser engraving is applied (Kuktaitė et al., 2020a). Regardless of a large supply of wood materials available for engraving in the market, yet not all wood is suitable, as the quality and the final result depends on the type of wood, its physical and mechanical properties, in particular. Thus, an appropriate selection of the individual parameters of wood processing according to the type of board plays a vital role aiming to achieve a desirable result. Barnekov et al. (1986) claim that one of the major factors that determines laser and wood interaction is the nature of the wood chips, its density, moisture content, separated concentrated materials and optical properties (Gurau et al., 2017). CO_2 laser-adapted plywood is usually made from birch wood, which is resistant to atmospheric effects, and maintains the stability of properties under the influence of various external factors. Birch plywood consists of several high-quality full-sized veneer sheets of birch wood glued together. The sheets are glued with strong glues so that the texture of the adjacent layers is in an opposite direction. High temperatures and high pressure are used in the production of the plywood (Varanavičienė et al., 2017). Plywood is a strong and hard (robust) material, resistant to deformation and abrasion, with properties superior to ordinary wood. Its surface fibres are smoothed, there are no obvious defects in the wood structure, texture is uniform without additional contrasting shades of the surface, so when engraving a larger area, a more uniform solid colour tone is obtained. However, various patterns of wood present in the glued plywood do not allow to achieve 100 % uniform colour tone over the entire area of the object, but due to the smoothness of the plywood surface, more intense and more uniform colour tones of different intensity are obtained in comparison to homogenous structure of fibreboard.

The quality of engraving depends on the thickness of wood, density, moisture content and glue (Petru et al 2014). Petru et al. (2014) found in the study that a low laser power cannot pass through the entire thickness of wood plywood, whereas a high laser power burns the wood. Laser used for the wood processing darkens the colour of the plywood surface, as the colour may range from light brown to black. Lin et al. (2008) investigated the effect of movement speed ratio and laser radiation power on the depth and colour difference of the MOSO® bamboo laminate and found that the higher power of radiation and lower speed of movement, the higher values in colour difference and the greater depth (cited from Gurau et al., 2017). The study showed that the above-mentioned factors can be predicted and evaluated by regression analysis. Li et al. (2020) state that the principles of laser beam operation such as laser power, movement speed and radiation width have a significant effect on the colour components ΔL and ΔE of bamboo surface. Absolute values increased in the presence of a higher laser power, but decreased with increasing speed of laser beam movement and operating range. The relationship between laser beam operating parameters and colour digital coordinates ΔL and ΔE was determined. This method can be applied in order to achieve a desirable colour or different colour choices (Li et al., 2020). Based on the study carried out by G. Kuktaitė et al. (2020b), it was found that in the presence of different parameters of laser beam speed and radiation power, samples of close colour tones on birch plywood can be obtained, e.g. differences in ΔE values do not exceed 3, which corresponds to the limits of the imperceptible colour difference of the observer's visual assessment. It was also found that the power of laser radiation has a greater effect on the changes of colour properties of wood plywood than movement speed. The value of ΔE is proportional to the laser radiation power, given the laser beam moves at a maximum speed of 600 mm/s. The value obtained in the samples was the lowest, as a laser beam moved faster through the sample width. The highest ΔE value was obtained when the lowest speed was chosen, as a laser beam moved at a lower speed, and the microstructure of wood plywood exposed to a laser beam for a longer period was more damaged (G. Kuktaitė et al., 2020b).

Irawan et al. (2008) investigated how CO_2 laser creates (destroys) microstructures due to the mechanism of photothermal ablation. It was found that a 10,6 μm laser beam is absorbed by fibrous materials, later on, heats, melts and vaporises them. Due to this process applied, a void is left on the wood.

The depth of microstructures is determined by the properties of material, the power of laser radiation, the number of the laser passes and the speed of movement of the laser beam. The depth of microstructure linearly depends on the set of parameters of the laser beam, yet the laser power has to be optimised taking into consideration properties of the material (Klank et al., 2002, cited from Irawan et al., 2008). A study by Gurau et al. (2017) found a correlation between change in colour of wood (difference in colours measured by ΔE) and surface roughness (measured roughness parameters Ra, Rq, Rt, Rk, Rpk, Rvk*)*. Such correlations can be useful in selecting power and speed combinations that can provide the minimum surface roughness for the selected colour change (Gurau et al., 2017). Gurau et al. (2017) claim that roughness of the surface and total colour difference ΔE increased with laser power and decreased with the scanning speed, respectively. When the speed was higher than 300 mm/s, a slight difference in colour was observed, whereas surface roughness remained the same (Gurau et al., 2017). *Pritam* (2016) found that the arithmetic roughness average Ra decreases as movement speed and laser power increases. To reach deeper cavities, but at a lower speed, it is recommended to increase the frequency of laser scanning at lower power and higher speed of movement (Pritam, 2016).

Based on the study carried out by G. Kuktaitė et al. (2020a), the analysis of the ΔE results showed, that the change of laser technological parameters has an effect on colorimetric indices of the plywood and processes of laser ablation, as a deep graphic image is obtained in a material with different morphological properties. In the overview on laser engraving done by Patel et al. (2015), the influence of process parameters including laser power scanning speed and laser frequency on engraving and surface roughness is emphasized (Gurau et al., 2017). As noted in the article, information on the effect of different laser technological parameters on the morphological properties of the material surface, radiation ablation processes, set of the concentrated laser beam parameters that destroys the structure of material surface and application of clearly defined visual production is insufficient.

Based on the aforementioned data, it can be stated that the selection of optimal parameters of technological processes becomes a key issue when transferring the computer-generated image onto the plywood. Thus, the aim of this study is to analyse the effect of technological parameters of CO_2 laser radiation (power and speed) on the morphology of the glued birch plywood and colour, and to determine the correlation between ΔE and Ra parameters, applying the method of morphological metrology and the comparative spectrophotometric analysis of surface colour tones.

Methodology
A vector layout was developed using Adobe Illustrator software. The layout was imported into RDWorks V8computer software, which has an interface with Bodor BCL-MU CO_2 laser, used for engraving objects. Laser beam operating field corresponded to the size of the chosen objects. Bodor BCL-MU CO_2 laser with a beam wavelength of 10.6 μm and an engraving speed of 0–60000 mm/ min. Minimum engraving area of 1 mm × 1 mm. To ensure an appropriate operating environment of the device, 18 °C room temperature and 41 % humidity was maintained (Bodor User Manual for BCL-MU Series Laser Machine, 2019).

In this study, a birch plywood sheet of 500 × 300 mm specially adapted for cutting and engraving was chosen for the analysis. Composition and parameters of the analysed sample: 100 % birch, 3 mm of thickness, rigid thickness tolerance of plywood (+0,3 / –0,3), density 640–700 kg/m^3, high-quality full-size veneer inside and outside, a minimum number of defects in all layers. Based on the measurements carried out by G. Kuktaitė et al. (2020a), specific areas of the sample affected by the combination of power and speed parameters were selected for a more detailed analysis. The analysed area of the sample consisted of a number of 18, 50 × 50 mm sections exposed to laser radiation. To carry out an analysis, appropriate combinations of power and speed of 20 % 200 mm/s, 20 % 240 mm/s, 100 % 600 mm/s were selected. In the samples, marked 200v, 240v and 600v, changes in colour tones and microstructure of the plywood surface were observed.

For the analysis of change in colour tones, X-Rite I1 Pro spectrometer was used to carry out measurements. The measurement data are presented as the change in ΔE in compliance with ISO/CIE 11664-4:2019 standard (Lithuanian Standards Board, 2019). Standard ISO/CIE 11664-4:2019 regulates a mathematical formula for estimating the change in colour between two objects compared. The value of ΔE determines the change between L*a*b* coordinates corresponding to the position of colour tones in the colour space. The values of ΔE for visual assessment are regulated by the standard. The result of the observer's visual assessment depends on the ΔE value of the digital colour coordinate difference. Given $\Delta E < 3$, the difference in colours is almost imperceptible. When $3 \leq \Delta E \geq 6$, difference in colours is observed, when two objects are adjacent. When $\Delta E > 6$, colour difference is visible by the naked eye, and when the value increases, a significant colour contrast is observed. Colour measurements were performed at five points on the sample.

Roughness can be considered as a major criterion describing the quality of the treated surface, since it determines further methods of surface finishing, possible application and appearance. The values of surface roughness are regulated by the standard 4287:1997. The standard covers main indicators as follows: the arithmetic average of the profile deviations Ra, the average roughness Rz, etc. (Baskutis et al., 2019). The arithmetic average of the absolute values of the profile roughness Ra and the height of micro-roughness Rz were evaluated in three directions of wood fibre: along the wood fibre, across the wood fibre, and at an angle of 45º, measured at five points. The profilometer PCE-RT 1200 was used to determine the surface morphology of the birch plywood. The profilometer operates according to the touch method in accordance with ISO 3274. The RC wave filtering method was chosen, setting an expected marginal length 2,5 mm, measuring zone 10 mm.

The quality of the structural properties of plywood was evaluated by capturing images using Invenio 5SII camera with the installed optical microscope Motic SMZ-171. The surface image of the analysed sample was magnified 2 × 2 × 10 times with a resolution 2560 × 1922 pixels. Live image speed is up to 48 fps. The 3D optical system MicroCAD Lite was used to record deformations of the surface and obtain precise classification results (see Fig.1). The distance to the measured surface of the sample (object) was 3 cm, resolution 0,1 µm, measurement resolution 748 × 480 pixels, and the measurement zone covered 1,8 × 1,2 mm area. The 3D MicroCAD optical system works with ODSCADGFM 3D measurement and analysis software. The relief of the sample surface was scanned with the camera and the 3D photograph was taken. The selected optical scanning methods allowed to determine a more precise microstructure of the plywood surface.

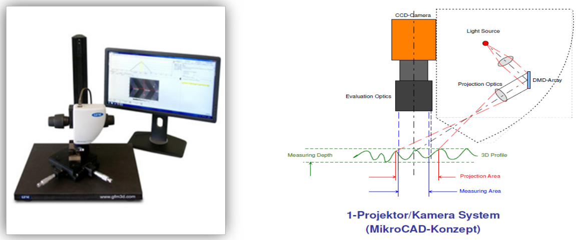


Fig.1 Optical 3D MicroCAD Lite measurement device and projector/ camera system (MicroCAD concept)(Lmi technologies, 2021)

Result analysis

Birch plywood was treated with a gas CO_2 laser by selecting different parameters (Fig.2). The power and movement speed of the laser beam were selected based on the colour tone palette developed by G. Kuktaitė et al.(2020a), designed to determine the value differences of colour tones on plywood, when the value differences correspond to ΔE < 3 limits. The colour differences of the samples obtained by selecting the following laser speed 600 mm/s and 100% power (600v), speed 200 mm/s (200v) and 240 mm/s with 20% power (240v), were insignificant. Yet, the effect of laser applying such technological parameters on the morphological properties of the plywood surface was unknown. With the increasing laser speed and power, a smoother surface of the plywood is obtained, thus a combination of 600 v technological parameters was chosen as the reference sample (Table1).

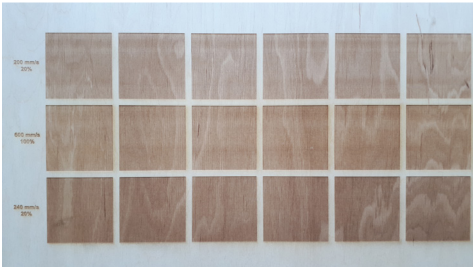


Fig.2 Samples of birch plywood after exposure to radiation

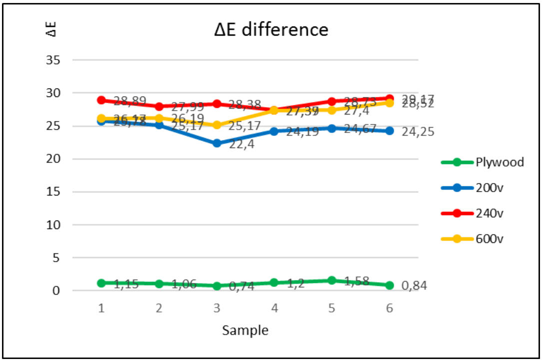
The effects of radiation power and beam speed were analysed using a spectrophotometric method. The difference in colour tones between radiation-exposed samples and unaffected plywood was evaluated by ΔE vector values of digital colour coordinate differences, presented in Table 1. The table shows five ΔE arithmetical averages of six engraved samples on the plywood, where the average of the averages is derived and the difference of the averages of 200v, 240v and 600v is calculated.

Table 1. Colour difference ΔE on glued plywood exposed to radiation

Process	**Laser parameters**		**ΔE difference, sample**						**ΔE**	
	Speed, mm/s	**Power, %**	**1**	**2**	**3**	**4**	**5**	**6**	**Average**	**Difference between 600v**
Plywood	Unaffec-ted	Unaffec-ted	1,15	1,06	0,74	1,2	1,58	0,84	1,1	25,7
200v	200	20	25,78	25,17	22,4	24,19	24,67	24,25	24,41	2,39
240v	240	20	28,89	27,99	28,38	27,39	28,73	29,17	28,43	1,63
600v	600	100	26,17	26,19	25,17	27,37	27,4	28,52	26,8	0

Having analysed the obtained ΔE values, it was observed that the change of technological parameters affects the colorimetric indices of the plywood surface. The ΔE value differences are insignificant and fall within the imperceptible limits of the observer's visual assessment, e.g. ΔE < 3, but their differences indicate that the speed of beam movement had an effect on the colour tone of the plywood surface. The average value of ΔE obtained at a speed of 240 mm/s for laser beam was 16% higher than moving at the speed of 200 mm/s, yet compared to the average value of ΔE at the speed of 600 mm/s, the difference of the ΔE value average is 0,76 smaller than between the 200v and 600v samples. Figure 3 presents values of the average differences that confirm that the difference in colour tones is smaller between the 600v and 240v samples.

a)



b)

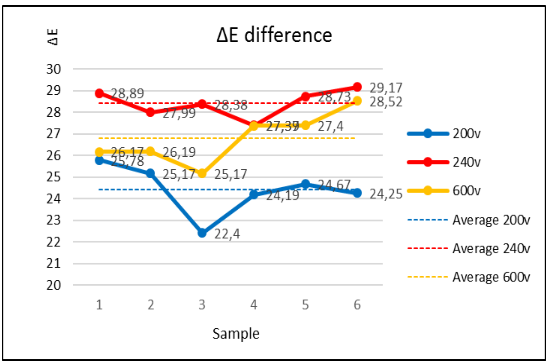
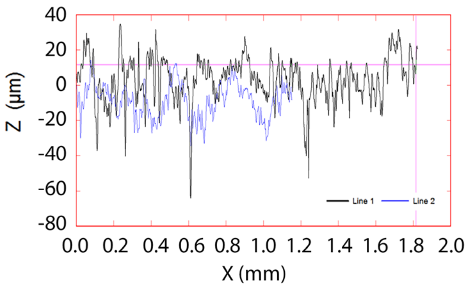


Fig 3. Colour difference ΔE on glued plywood exposed to radiation:
a) ΔE change in plywood affected and unaffected by laser b) ΔE average values

The metrological study method of surface morphology was used to compare structural surface properties of laser-untreated glued plywood with the different parameters affected by engraving process on the fibreboard samples. In addition, the maximum changes in the height of micro-roughness Rz and the arithmetic means Ra of the profile roughness Ra were determined. The data of arithmetic means obtained in the study are given in Table 2.

In the course of the study, it was observed that the speed of beam movement and radiation power influenced the ablation process. Comparing the surface of the unaffected plywood with the surface that was affected by the combination of laser technological parameters, the increase in the values of roughness indices Ra and Rz was insignificant in transverse, longitudinal and 45°angle wood fibre directions in the glued, laser-exposed plywood. The lowest roughness was found in 600 v samples affected by a combination of laser parameters, the highest roughness in 200 v samples, whereas data values of 200 v samples were close to the values of 600 v samples. Figure 7 shows how the surface roughness of fibreboard alters during the laser engraving process in the longitudinal and transverse directions of wood fibre.

a)



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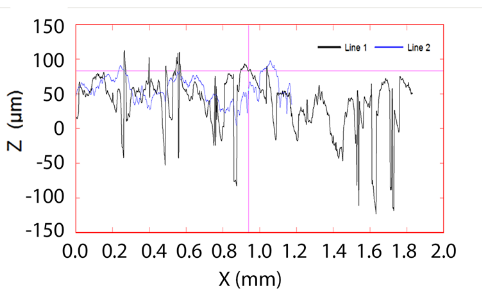
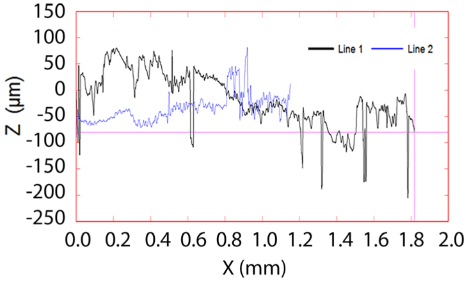


c)



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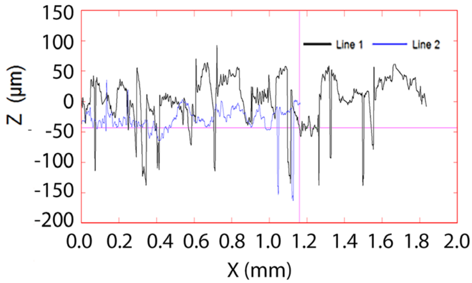


Fig. 4 Difference in roughness in the longitudinal and transverse direction of the plywood fibre
a)Unaffected plywood, b) 200v sample, c) 240v sample, d) 600v sample

Percentage values are used to determine the increase in roughness. Comparing plywood exposed to 20 % radiation power, but with a beam moving at different speeds (200 mm/s and 240 mm/s), it was determined an insignificant, yet greater effect of speed on morphological surface properties, e.g. in the 200v samples, when a laser beam was exposed in the longitudinal direction of wood fibre, the arithmetic average values Ra are 1,2 % higher, corresponding to the absolute difference 0,12 µm, whereas Rz values are 1,4 % higher (absolute difference 0,38 µm); in the transverse direction of wood fibre Ra – 10,6 % (absolute difference 1.51 µm), Rz – 10.9 % (absolute difference 4.4 µm) higher. This proves that a smoother surface of plywood was obtained at 6,7 % higher speed (240 mm/s).

Table 2. Morphology of plywood surface after exposure to radiation

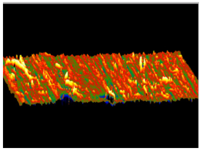
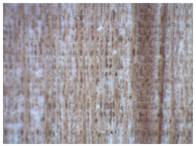
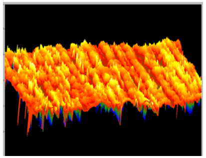
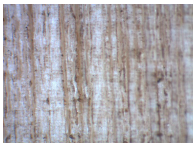
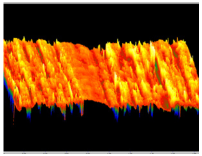
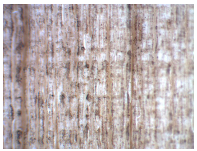
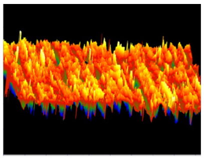
Process	Microscopic image	3D Microscopic image	Ra, µm			Rz, µm		
	Structure of glued plywood	Morphology of plywood surface	Along the wood fibre	Across the wood fibre	45° angle	Along the wood fibre	Across the wood fibre	45° angle
Unaffected plywood			2,08	5,41	5,33	5,89	15,28	15,05
200v-200 mm/s, 20%			9,84	15,83	14,17	27,88	44,81	40,09
240v-240 mm/s, 20%			9,72	14,32	14,87	27,50	40,41	42,06
600v-600 mm/s, 100%			9,65	13,78	15,33	27,28	38,97	43,36

Table 3. Comparison of the increase in surface roughness of fibreboard between 200v and 240v samples after exposure to radiation

Indices	Surface roughness					
	Along the wood fibre			Across the wood fibre		
	200v, µm	240v, µm	Increase, %	200v, µm	240v, µm	Increase, %
Ra	9,84	9,72	1,24	15,83	14,32	10,55
Rz	27,88	27,50	1,38	44,81	40,41	10,89

The obtained values of the surface roughness in the 200v and 240v samples are very close to the selected reference sample of 600v, it can be stated that the surface morphological data between the 240v samples and the reference sample differ the least in the longitudinal direction, when Ra – 0.7% (absolute difference 0.07 µm), Rz – 0.8% (absolute difference 0.22 µm), in the transverse direction Ra – 3.9% (absolute difference 0.54 µm), Rz – 3.7% (absolute difference 1.44 µm). The speed of beam movement varied by 60% in the samples, radiation power by 80%, yet technological parameters of laser operation did not have a significant influence on the changes in the results obtained.

Table 4. Comparison of the increase in surface roughness of plywood in 200v, 240v and 600v samples after exposure to radiation

Indices	Surface roughness						Surface roughness					
	Along the wood fibre			Across the wood fibre			Along the wood fibre			Across the wood fibre		
	200v, µm	600v, µm	Increase, %	200v, µm	600v, µm	Increase, %	240v, µm	600v, µm	Increase, %	240v, µm	600v, µm	Increase, %
Ra	9.84	9,65	1,97	15,83	13,78	14,88	9,72	9,65	0,73	14,32	13,78	3,92
Rz	27,88	27,28	2,2	44,81	38,97	14,99	27,50	27,28	0,81	40,41	38,97	3,7

Having analysed the general data on changes in colour tones and surface roughness, the best correlation was observed between the analysed samples. It was found that the average values of ΔE and surface roughness of the 600v correlate with 240v sample parameters, when the samples are exposed to a combination of laser parameters. Thus, it can be stated that 600 v samples correlate with 200v samples, but the differences in the obtained values in the 600v sample are larger than in 240v samples.

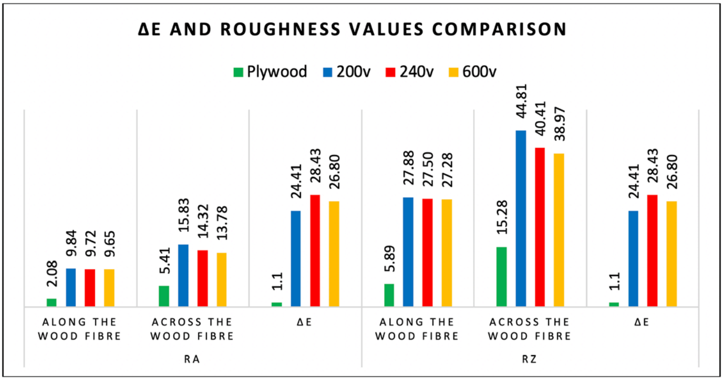


Fig.5.Comparison of average values between ΔE and surface roughness

Consequently, in the production of visual objects using laser engraving technology, and in order to obtain the desirable colour tone in glued plywood, different combinations of technological parameters of laser operation (radiation power, speed of laser beam movement) can be applied, ensuring optimal reduced surface roughness of the material. The study showed that the average values of ΔE with a minimum difference in morphological properties were obtained using combinations of technological laser parameters applied onto 600v and 240v samples, corresponding to the limits of the small range of $25 \leq \Delta E \leq 30$ colour change. It can be claimed that the minimum occurrence of roughness is proportional to the minimum change in colour tone. However, the 600v sample was produced using 100 % laser power, whereas the 240v sample 20 % laser power. Considering the speed of laser movement and the amount of energy consumed, it can be stated the production of the second sample required a lesser amount of energy consumption, while the colour obtained of the latter sample was analogous ($\Delta E<3$) to the sample produced at a higher speed.

This study can be further developed to investigate the influence of radiation on the structural properties of the finishing processes, the shape of graphic objects of different areas and their combinations, compatibility with other printing technologies, and processes of the material ablation. Based on the obtained results, certain proposals can be made for the production of graphic objects, taking into consideration the proportions of time and CO_2 laser gas consumption and selection of a more efficient production method.

Conclusions

1. Changes in the technological parameters of laser affect the colorimetric indices of the surface of glued plywood. Insignificant differences in ΔE were obtained fall within the imperceptible limits of the observer's visual assessment, e.g. ΔE < 3, but their differences indicate that the speed of the beam movement influenced the colour tone of the fibreboard.

2. Comparing the surface of the laser-unaffected surface of the plywood with the surface that was exposed to the combination of the technological laser parameters, it was found, that the values of surface roughness Ra and Rz, increased by 2.7 time in the transverse direction of wood fibre, 4.7 times in the longitudinal direction, and 2.8 at 45° angle, accordingly.

3. The minimum change in the movement of the laser beam has an impact on the morphological properties of glued plywood surface. The increase in the speed of laser beam by 6.7 % had a smaller effect on the ablation process, as the obtained microstructure of plywood surface was smoother 1.2 % in the longitudinal direction, in comparison to 10.6 % in the transverse direction.

4. The average values of ΔE that correspond to the visual assessment requirements of the observer (when ΔE < 3) were obtained with a minimum difference of morphological properties, when appropriate combinations of technological parameters of laser beam 600v and 240v. Given ΔE=1,63 change, the smallest difference in the morphological indices of the surface is obtained, when Ra – 0.7 % and Rz – 0,8 % in the longitudinal direction, and Ra – 3,9 % and Rz – 3,7 % in the transverse direction. This determines the choice of parameters depending on the laser power consumption.

5. To obtain the desirable colour tone in the glued plywood, different combinations of technological parameters of laser operation (radiation power, speed of laser beam movement) can be applied in the production of visual objects, be means of laser engraving technology, ensuring optimal surface roughness of the material. The minimum roughness is proportional to the minimum change in colour tone, when plywood is processed at 240 mm/s speed and 20 % power, and at 600 mm/s and 100% laser power.

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