Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2013, Article ID 123085, 7 pages
http://dx.doi.org/10.1155/2013/123085

Research Article

Laser Treatment of Wood Surfaces for Ski Cores: An Experimental Parameter Study

Alexander Petutschnigg,[1,2] Michael Stöckler,[3] Florian Steinwendner,[3] Julian Schnepps,[3] Herwig Gütler,[3] Johann Blinzer,[3] Helmut Holzer,[4] and Thomas Schnabel[1]

[1] *Salzburg University of Applied Sciences, Markt136a, 5431 Kuchl, Austria*
[2] *BOKU University of Natural Resources and Life Sciences, Konrad Lorenzstraße 24, 3430 Tulln, Austria*
[3] *Holztechnikum kuchl, Markt136, 5431 Kuchl, Austria*
[4] *Atomic Austria GmbH, Lackengasse 301, 5541 Altenmarkt, Austria*

Correspondence should be addressed to Alexander Petutschnigg; alexander.petutschnigg@fh-salzburg.ac.at

Received 2 May 2013; Revised 8 August 2013; Accepted 17 August 2013

Academic Editor: Gongnan Xie

Recently, the production of skis with wooden cores has increased due to changes in customer awareness concerning ecological issues and rising raw material costs for mineral oil resources. The preparation of ski surfaces is one of the main expense factors in the production of skis. Thus, one perspective of the AMER SPORTS CORPORATION is to treat wood surfaces with laser beams to develop new aesthetic possibilities in ski design. This study deals with different laser treatments for samples from various wood species: beech, ash, lime, and spruce. The parameters investigated are laser beam intensity and number of laser points on the surface. To evaluate the aesthetic changes, the CIELab color measurements were applied. Changes in the main wood components were observed by the Fourier transform infrared spectroscopy (FTIR) using an ATR (attenuated total reflectance) unit. The results show that the laser treatments on wood surfaces have an influence on wood color and the chemical composition. Especially the intensity of laser beams affects the color changes in different patterns for the parameters observed. These findings will be useful to develop innovative design possibilities of wood surfaces for ski cores as well as for further product design applications (e.g., mass customization).

1. Introduction

Wood surface manipulation is an important issue in forest products industries. Depending on the product and the process, the treatments are used to change mechanical, physical, or biological properties of the surface as well as aesthetic properties. In ski industries, surfaces guarantee the most visible differentiation between products. Therefore, not only the technical requirements but also the aesthetic requirements are essential for the final graphics layer. However, the production of a colored surface for skis is cost-intensive. For this reason, one aim of ski production is to apply the graphics directly on the core. One possibility to change the appearance of wooden surfaces is laser engraving.

The use of lasers in forest products industries is not new (compare the descriptions in [1, 2]). The influence of different laser treatments on wood surfaces was analyzed by Panzner et al. [3] and Parameswaran [4]. They describe the influence of the laser treatment on the wooden structure for beech (*Fagus sylvatica*) and pine (*Pinus spp.*) wood. Furthermore, Kubovský and Kačik [5] and Kačík and Kubovský [6] showed that different dosages of irradiation on maple (*Acer pseudoplatanus*) and beech (*Fagus sylvatica*) wood with a CO_2 laser led to different chemical changes of the material. Wust et al. [7] analyzed the absorption and the influence of the irradiation with an Nd:YAG-laser and a CO_2 laser for beech (*Fagus sylvatica*), spruce (*Picea abies*), and sapelli wood. They realized that the CO_2-laser needed a shorter irradiation time to achieve the same effect compared to the Nd:YAG-laser. The effect of feed speed ratio and laser power on the engraved depth and the color difference for Moso bamboo (*Phyllostachys edulis*) lamina was analyzed by Lin et al. [8].

They concluded that the color changes are influenced by the laser power. Leone et al. [9] worked on the influence of laser parameters on engraving depth for walnut (*Daniela walnut-Guibourltia ehie*), mahogany (*Swieitenia mahogani*), chestnut oak (*Quercus petraea*), poplar (*Populus alba*), and pine (*Pinuspinea*). They proclaimed the necessity of parameter definitions for specific wood species to achieve good laser engraving results. For the application of laser engraving, the knowledge of the behavior of wood species in laser irradiation is crucial. Laser treatment of the wooden ski core before lamination with epoxy resin and glass fiber materials could be one possibility to develop new ski surfaces with attractive designs. For this, no further chemical treatment or additional pigments are necessary for the graphics. This process would also be very ecological and an interesting solution for cradle-to-cradle designed ski cores.

The aim of this study is to analyze the visual changes of laser treated wood surfaces. This analysis focuses on the color changes and chemical modifications due to laser treatment for four various wood species. In order to induce the desirable color changes through the industrial laser applications on the wood surfaces, the following tasks were defined.

Task 1. Analyze the behavior of different wood species according to the changes of the color through laser treatment. This is necessary as wooden ski cores often consist of a combination of different wood species which are combined.

Task 2. Analyze different laser parameters according to their influence on the color achieved by laser treatment. As the treatment should be as efficient as possible, it is important to note if changes in the machine parameters will change the resulting wooden color differently.

Task 3. Analyze the chemical changes in wood components caused by laser beam irradiation. This is necessary to obtain important information about the possible surface modification and activation of various wood species due to industrial laser treatment. This modification may influence the subsequent product coating.

2. Material and Methods

For the tests, four different wood species were chosen.

Beech (*Fagus sylvatica*) is a diffuse porous hardwood species with a high modulus of elasticity (MOE) of 14000 N/mm^2, a high modulus of rupture (MOR) of 120 N/mm^2, and a high density of 0.71 g/cm^3 (DIN 68344) compared to other European wood species. Beech wood is used in ski production especially for its good mechanical properties and the good availability in Austria as it is the most common hardwood species [10], and it is a widely used species in ski cores for its high MOE.

Lime (*Tilia platyphyllos*) is also a diffuse porous hard wood species like beech but lime has a lower MOE (9000 N/mm^2), MOR (98 N/mm^2), and density (0.53 g/cm^3) compared to beech wood. Additionally lime wood can be processed easily [11] and therefore, it can be applied in skis to reduce weight and allow 3D shaping.

Ash (*Fraxinus excelsior*) is a ring porous hardwood species which has a high MOE (13000 N/mm^2) and MOR (105 N/mm^2) and a density of 0.70 g/cm^3 (compare [12]). Ash is the traditional wood species for ski core production.

Spruce (*Picea abies*) is a coniferous wood species which has a high share of the total forest area in Austria. This wood species is usually not used in ski production, but due to the high importance for Austrian wood industry and the interest of the research team in the behavior of this wood species concerning laser treatment, it has been decided to include this species in the study. Spruce has a MOE of 11000 N/mm^2, a MOR of 80 N/mm^2, and a density of 0.46 g/cm^3 [12].

For each wood species, four samples with a length of 200 mm and a cross section of 20 mm × 20 mm were cut. The longitudinal cuts were made in a way in which the radial and tangential surfaces of the cut wood could be seen within the perpendicular sides of the samples.

2.1. Laser Treatment. The laser used was a Trotec CO_2-laser (wavelength of 10.6 μm) Speedy 500 (http://www.troteclaser.com/) with a 2.5 inch lens. This lens has an optimal distance during the laser engraving and a high accurateness regarding the treatment area. The maximum power of this laser is 120 Watt. For laser treatment, two parameters were varied, namely, the intensity (controlled by the laser power) and the laser points applied per inch. The laser speed was kept constant for this study. To be able to measure the color of the treatment, a rectangular field of 10 mm × 10 mm was irradiated with the laser.

In our study, the following laser parameter combinations were chosen.

(1) No laser treatment.

(2) Intensity low (40 Watt) and 333 laser points per inch.

(3) Intensity low (40 Watt) and 1000 laser points per inch.

(4) Intensity high (120 Watt) and 333 laser points per inch.

(5) Intensity high (120 Watt) and 1000 laser points per inch.

For each wood species, fifty surfaces were used to evaluate the changes due to laser treatments.

2.2. Color Measurement. The color was measured by a Mercury 2000 spectrophotometer (Datacolor) with a measurement spot diameter of 8 mm. For measurements, a standard illuminant D_{65} and a 10° standard observer were chosen. The color was determined according to the Commission International de l'Eclairage (CIE) $L^*a^*b^*$ color space by the coordinates L^*, a^*, and b^* as described in detail by Wyszecki and Stiles [13].

2.3. FTIR Spectroscopic Measurement. The surfaces of the four different wood species samples were analyzed with a Perkin-Elmer Frontier FTIR using an ATR Miracle diamond crystal accessory. The spectra used 32 scans with a resolution of 4 cm^{-1} in the wave number range between 4000 and 600 cm^{-1}. Three single spectra per sample were average. The FTIR spectra used for analysis of the laser treatment effects were bascline corrected and normalised with respect to the band at 1370 cm^{-1}. This absorbance band shows minimum changes after the laser treatment, and it is corresponded to the C–H deformation vibrations.

2.4. Data Analysis. For the three color values and the treatments, the mean and the standard deviation are calculated for descriptive statistics. To prove differences, the t-test (compare [14]) was applied. However, normally distributed data are necessary; this was analyzed by the Levene test if the variation of the data is equal. If the assumption of equal variation was not fulfilled, the adapted t-test (compare [14]) for heterogeneous variance was used.

3. Results and Discussions

A comparison of the results for treated and untreated wood surfaces was attained in compliance with the research task. The results are shown separately for the four different wood species samples and for L^*, a^*, and b^*, respectively.

3.1. The Influence of Laser Treatment on Wood Color. The laser treatment was carried out successfully for all samples from various wood species. Figure 1 shows a comparison between untreated and laser treated surfaces, while only the rectangular fields of 10×10 mm^2 were treated and the flanking surface remained untreated. On visual inspection, the wood species show a different appearance depending on laser treatment, and it was clear that the treated wood became darker. This behaviour should also be consistent with a decrease in L^* values (Figure 2).

The treatment with the highest power input (120 Watt) and 1000 points per inch led to strong changes in the material properties of the sample. It could be observed that the sharp border between untreated and treated surfaces disappears (e.g., arrow on the ash sample in Figure 1). Also, glossy seeming surfaces can be determined. Parameswaran [4] mentioned this phenomena as a melting (e.g., caramelization) of the cellulose. Also, Leone et al. [9] observed a melting with strong carbonization on various wood surfaces by using high laser intensity. Therefore, it could be assumed that the laser power was too high, resulting in a sharp rise of temperature in a short time period. This is in consistance with the findings by Back [15] that a melting without combustion and carbonizing can only be achieved if the heating and cooling occurs in a short time. Thereby, the thermal behavior of each wood constituent (e.g., cellulose, polyosen, and lignin) differs, while the polyosen is firstly degraded, lignin and cellulose are more stable against higher temperature [15–17].

To give an impression of the data distribution, the effect of the laser treatment on L^* is shown in Figure 2.

It can be seen that with an increment in the intensity as well as an increase of the number of laser points per inch, the L^* value decreases and the wood becomes darker. However, high laser intensity treatment with 333 points per inch shows comparable L^* value to the low intensity treated samples with 1000 points per inch. Therefore, the t-test was used to prove the uniformity of the L^* values of the samples for these laser parameter settings (Table 1).

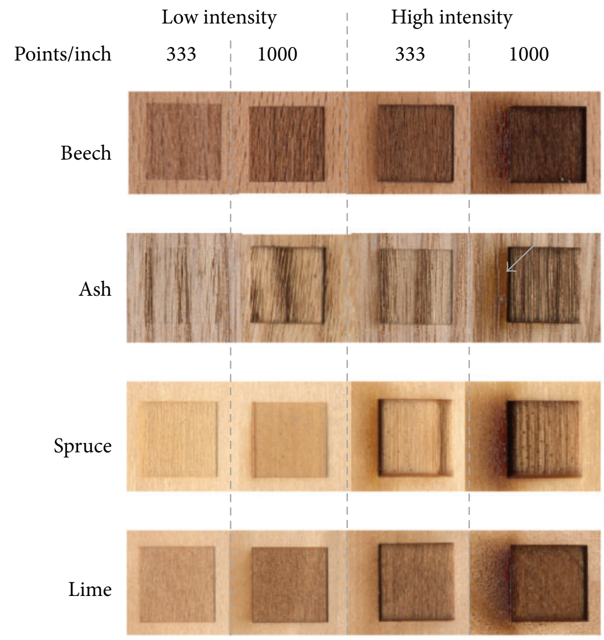

Figure 1: Images of laser treatments on the wood species with different laser intensities (a rectangular field of 10 mm × 10 mm was irradiated with the laser) from up to bottom, beech, ash, spruce, and lime.

Table 1 shows that increasing intensity does not lead to a stronger darkening (decrease of the L^* value) than increasing points per inch for all wood species. Nevertheless, for most experiments the higher impact of the intensity compared to the points per inch is significant.

Accordingly, it can be noted for task 2 that the laser parameters are influencing the resulting L^* value differently. Thus, the process parameters have to be adjusted according to the target L^* value change.

To evaluate the influence of the laser treatment on the color tone of the wood, the chromatic coordinates (a^* values and b^* values) were analyzed (Figure 3). The color changes are not linear for beech samples treated with low laser intensity and high laser intensity (Figure 3). It is very interesting that the color changes for low intensity and increasing laser points per inch follow in the opposite pattern compared to high intensity and rising laser points per inch. This behavior is of great advantage since not only the L^* value is influenced but also the color can be adjusted depending on the intensity of the laser beam.

The other results of ash, lime, and spruce wood samples do not show the same behavior in color tone changes as beech wood (Tables 2 and 3). A clear tendency of the discoloration through laser treatments cannot be determined. However, changes in color coordinates can also be obtained due to the laser treatments.

Table 1: Comparison of L^* values of two laser treatments (intensity low and 333 points per inch compared to intensity high and 1000 points per inch). Bold cells indicate significant differences with equal variance.

L^* values	Low intensity, 1000 points per inch		High intensity, 333 points per inch	
	Mean	Standard deviation (SD)	Mean	Standard deviation (SD)
Wood species				
Beech	**42.98**	**1.38**	**40.37**	**1.20**
Ash	**58.91**	**3.49**	**52.47**	**5.36**
Spruce	68.87	2.51	66.50	4.23
Lime	**56.41**	**2.84**	**51.57**	**2.96**

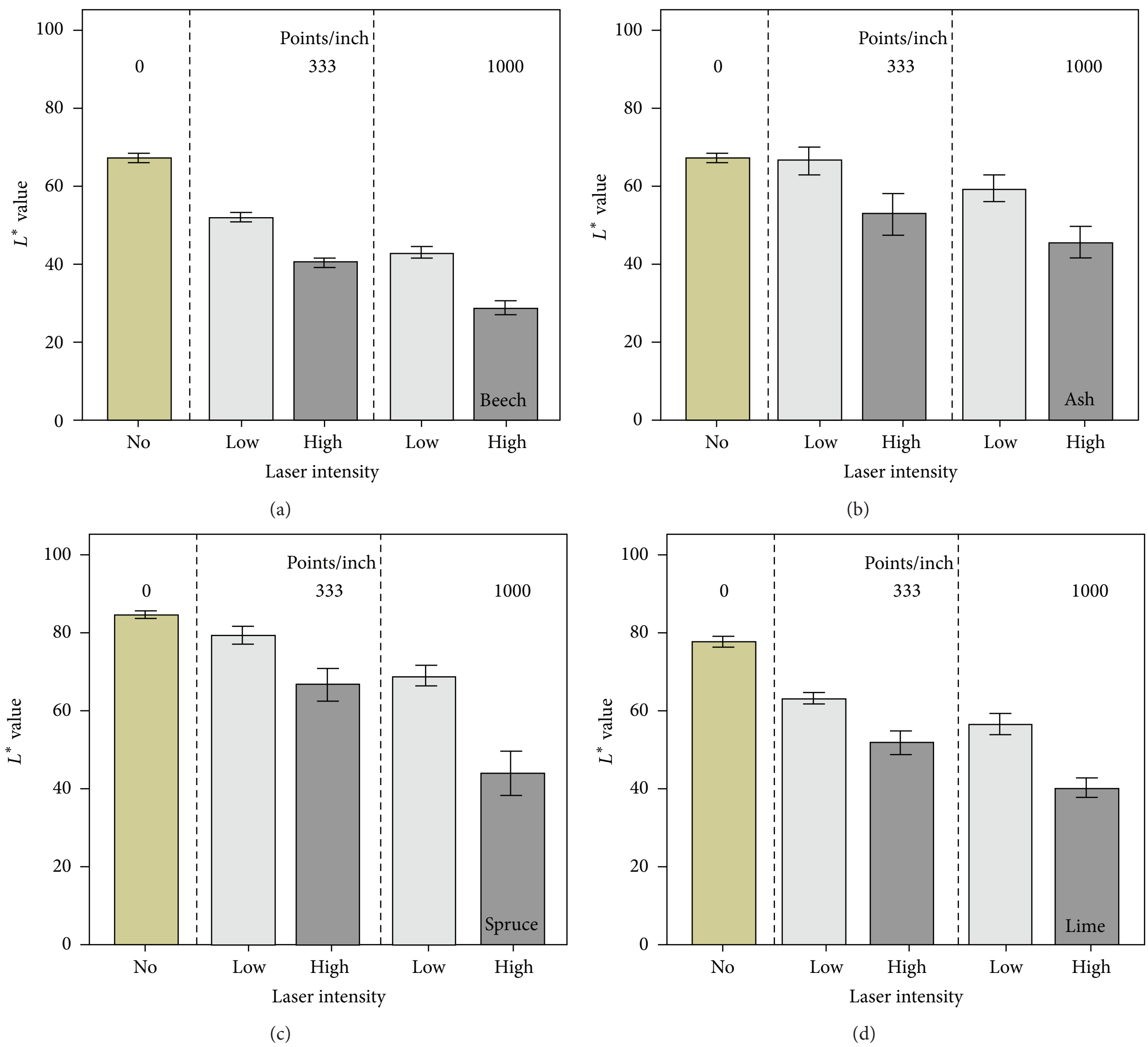

Figure 2: Results of the L^* value measurement for the wood species observed (for the different laser parameter settings).

3.2. The Influence of Laser Treatment on the Chemical Changes in Wood Components. The FTIR analysis has shown that chemical changes can be observed due to the laser beam irradiations depending on laser parameter settings. Panzner et al. [3] and Wust et al. [7] concluded that the effect of the CO_2 laser treatment on wood is mainly caused by thermal processes.

The chemical changes due to thermal modification in wood components occurred mainly in hemicelluloses/polyosen for hardwoods [18, 19]. This was also the first

Table 2: Comparison of a^* values of untreated wood surfaces with laser treated wood surfaces.

a^* values	No laser treatment	Low intensity treatment		High intensity treatment	
	Mean (SD)	333 points/inch Mean (SD)	1000 points/inch Mean (SD)	333 points/inch Mean (SD)	1000 points/inch Mean (SD)
Wood species					
Beech	11.63 (0.31)	12.66 (0.28)	13.27 (0.10)	11.84 (0.41)	10.63 (0.39)
Ash	7.13 (0.76)	6.59 (0.64)	7.58 (0.53)	8.96 (0.55)	8.31 (0.44)
Spruce	3.0 (0.5)	4.66 (0.78)	8.0 (0.59)	8.16 (1.18)	9.3 (0.65)
Lime	7.11 (0.57)	10.76 (0.42)	12.14 (0.69)	11.69 (0.51)	11.99 (0.66)

Table 3: Comparison of b^* values of untreated wood surfaces with laser treated wood surfaces.

b^* values	No laser treatment	Low intensity treatment		High intensity treatment	
	Mean (SD)	333 points/inch Mean (SD)	1000 points/inch Mean (SD)	333 points/inch Mean (SD)	1000 points/inch Mean (SD)
Wood species					
Beech	21.49 (0.45)	19.81 (0.48)	20.95 (0.41)	19.69 (0.42)	16.2 (0.86)
Ash	16.97 (1.45)	18.51 (0.83)	22.0 (0.55)	25.55 (1.63)	22.02 (1.49)
Spruce	23.09 (1.55)	28.75 (2.96)	34.16 (0.83)	32.93 (1.91)	26.99 (1.97)
Lime	23.86 (1.23)	25.39 (0.62)	28.81 (0.64)	26.81 (1.09)	25.37 (1.07)

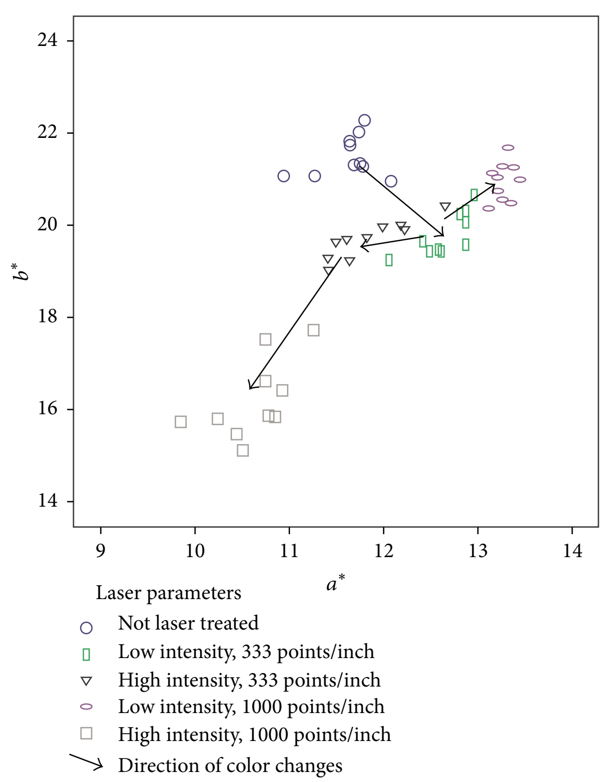

Figure 3: Influence of laser treatment on the color values (a^* and b^* values) of natural beech wood surfaces.

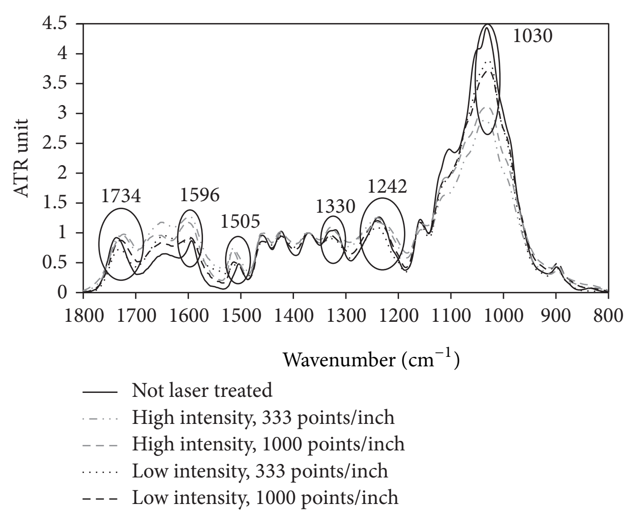

Figure 4: FTIR spectra of ash wood before and after various laser beam irradiations.

impression of the changes caused by laser beam treatments (Figure 4).

A difference between the IR spectra of laser treated and untreated ash samples was observed at the C–O band at 1242 cm^{-1}, which assigned to acetyl groups in hardwoods [18]. However, the intensity of the corresponding carbonyl groups at 1734 cm^{-1} did not change in the same pattern. The absorption intensity decreased after the laser treatment using the low intensity as well as the high intensity with 333 points per inch parameter settings, whereas with increasing the laser intensity and points per inch treatment, the band around 1734 cm^{-1} shows also a raise and a shift to wavenumber at 1727 cm^{-1}. This behavior is consistent with the chemical investigations of beech wood after laser irradiation by Kačík and Kubovský [6]. Therefore, new carbonyl groups might be generated resulting from a loss of acetyl groups of polyosen and contemporaneous with an increase of carbonyl groups through oxidation reactions of the lignin. A cleavage of the methoxyl groups of the lignin can be observed from the decrease in intensity at the vibration of the C–O (aryl-alkyl-ether) band around 1330 cm^{-1} [20]. The increase of the C=O groups in lignin can also be seen in the band at 1596 cm^{-1}, which is correspondent to aromatic skeletal breathing with carbonyl stretching vibration [21]. Moreover, the ascribed aromatic bands at 1596 and 1505 cm^{-1} show slight shifts, those provide evidence for the modification of lignin resulting from the thermal modification [18]. Funaoka et al. [22] concluded that the band at 1030 cm^{-1} of the alcoholic hydroxyl groups was also involved in the condensation reaction of side chains with phenyl groups. Therefore, a strong decrease in intensity at this band can be seen. This behavior of the chemical changes could also be observed in the beech and lime wood samples.

For spruce wood samples, some differences can be noticed (Figure 5). The decrease in intensity of the alcoholic hydroxyl groups at the band 1030 cm^{-1} was comparable to the hard wood samples and shows a condensation reaction of lignin [22]. The strong shifts in vibration of aromatic bands at 1596 and 1515 cm^{-1} was not found for the spruce samples. Also, the high decrease in intensity at the band around 1330 cm^{-1} was not observed in the laser treated hardwood samples, as softwood lignin has lower content of methoxyl groups than the hardwood one [23]. However, the intensities of the carbonyl groups at 1734 and 1596 cm^{-1} increased due to the laser treatment.

Summarizing, the laser treatment is able to change the functional groups of the wood component. Various treatments show varied changes in the intensity of the carbonyl groups vibration, but no dependence between laser parameter settings can be observed, except that the high laser intensity and 1000 points per inch treatment provides the strongest chemical changes for all wood species. However, for spruce wood samples, the smallest difference due to the laser treatment was observed compared to the hardwood species.

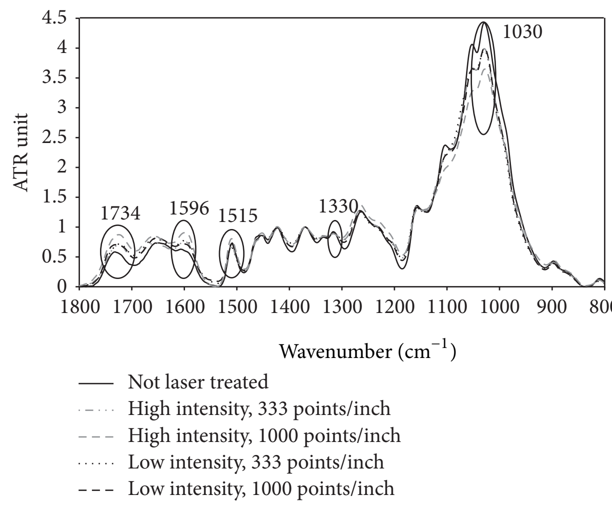

Figure 5: FTIR spectra of spruce wood before and after various laser beam irradiations.

4. Conclusions

The laser treatment of wood is not new; however, the existing studies mainly focus on the anatomical and chemical changes of the wood surface. Especially for wood species applied in ski cores; there is a lack of serious data about color changes due to laser treatment. Based on the results of this study, the three tasks defined were answered. It is possible to change the color of wood by laser treatment and the changes do not only occur by reducing the L^* value (darkening) but also the chromatic coordinates of the color can be affected. The changes of color are not randomly distributed, and it is shown; that the process parameters have a significant influence on the color changes. The behavior of the a^* and b^* values is different according to higher laser intensities.

Based on these findings, laser treatment on wooden ski cores can be used to change the appearance of the wood surface for design purposes. Therefore, the blackness and the color from yellow, red, and brown tones can be adjusted using different laser parameters.

Chemical reaction due to CO_2 laser treatment is indicated by the increase of the carbonyl groups in the FTIR spectra of laser treated wood samples. The reactions occur in the polyosen/hemicellulose and the lignin complex. New functional groups can influence the subsequent surface technology (e.g., coating).

In further investigations, logos and images will be applied by laser on real ski cores. The findings shown are a crucial step towards the successful application of laser treatment on wooden ski cores for aesthetic purposes.

References

[1] B. M. Broenstad, N. Auman, and K. Toennesse, “Laser applications in wood processing,” in *Proceedings of the 4th NOLAMP Conference*, Norges Tekniske Hoegskole, Sonderborg, Denmark, 1993.

[2] T. Orech and M. Kleskenova, Untersuchungen über die Holzbearbeitung mit Laserstrahlen. Drevo. 30. 324, 1975.

[3] M. Panzner, G. Wiedemann, K. Henneberg, R. Fischer, T. Wittke, and R. Dietsch, “Experimental investigation of the laser ablation process on wood surfaces,” *Applied Surface Science*, vol. 127-129, pp. 787–792, 1998.

[4] N. Parameswaran, “Feinstrukturelle Veränderungen an durch Laserstrahl getrennten Schnittflächen von Holz und Holzwerkstoffen,” *Holz als Roh und Werkstoff*, vol. 40, no. 11, pp. 421–428, 1982.

[5] I. Kubovsky and F. Kačik, “FT-IR study of maple wood changes due to CO_2 laser irradiation,” *Cellulose Chemistry and Technology*, vol. 43, no. 7-8, pp. 235–240, 2009.

[6] F. Kačík and I. Kubovský, “Chemical changes of beech wood due to CO_2 laser irradiation,” *Journal of Photochemistry and Photobiology A*, vol. 222, pp. 105–110, 2011.

[7] H. Wust, P. Haller, and G. Wiedemann, “Experimental study of the effect of a Laser beam on the morphology of wood surfaces,” in *Proceeedings of the 3rd International Symposium on Wood Machining*, Lausanne, Switzerland, 2007.

[8] C.-J. Lin, Y.-C. Wang, L.-D. Lin, C.-R. Chiou, Y.-N. Wang, and M.-J. Tsai, “Effects of feed speed ratio and laser power on

engraved depth and color difference of Moso bamboo lamina," *Journal of Materials Processing Technology*, vol. 198, no. 1-3, pp. 419–425, 2008.

[9] C. Leone, V. Lopresto, and I. de Iorio, "Wood engraving by Q-switched diode-pumped frequency-doubled Nd : YAG green laser," *Optics and Lasers in Engineering*, vol. 47, no. 1, pp. 161–168, 2009.

[10] Bundesamt für Wald, sterreichische Waldinventur 2007-2009. Bundesministerium für Land- und Forstwirtschaft, Umwelt- und Wasserwirtschaft. Wien, 2012.

[11] A. Teischinger, J. Fellner, and A. Eder, *Heimisches Holz*, Pro-Holz Holzinformation Österreich, 1997.

[12] DIN, *Kennwerte von Holzarten—Rohdichte, Elastizitätsmodul und Festigkeiten*, Deutsches Institut für Normung, 2003.

[13] G. Wyszecki and W. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae*, Wiley Classics Library, 2000.

[14] J. Hartung, *Statistik—Lehr und Handbuch der Angewandten Statistik*, Oldenbourg, München, Germany, 2005.

[15] E. L. Back, "Cellulose bei hohen Temperaturen: Selbstvernetzung, Glasumwandlung und Schmelzen unter Einwirkung von Lserstrahlen," *Das Papier*, vol. 27, pp. 475–483, 1973.

[16] Sandermann, W, and H. Augustin, "Chemische Untersuchungen über die thermische Zersetzung von Holz. Erste Mitteilung-Stand der Forschung," *Holz als Roh und Werkstoff*, vol. 21, pp. 256–265, 1963.

[17] Sandermann, W, and H. Augustin, "Chemische Untersuchungen über die thermische Zersetzung von Holz. Dritte Mitteilung: chemische Untersuchung des Zersetzungsablaufes," *Holz als Roh und Werkstoff*, vol. 22, pp. 377–386, 1964.

[18] E. Windeisen, H. Bächle, B. Zimmer, and G. Wegener, "Relations between chemical changes and mechanical properties of thermally treated wood," *Holzforschung*, vol. 63, no. 6, pp. 773–778, 2009.

[19] B. F. Tjeerdsma and H. Militz, "Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood," *Holz als Roh und Werkstoff*, vol. 63, no. 2, pp. 102–111, 2005.

[20] E. Windeisen, C. Strobel, and G. Wegener, "Chemische charakterisierung von thermisch belastetem holz: bestimmung der acetylgruppengehalts und FTIR-spektroskopie," *Holz als Roh und Werkstoff*, vol. 61, pp. 471–472, 2003.

[21] R. A. Kotilainen, T.-J. Toivanen, and R. J. Alén, "FTIR monitoring of chemical changes in softwood during heating," *Journal of Wood Chemistry and Technology*, vol. 20, no. 3, pp. 307–320, 2000.

[22] M. Funaoka, T. Kako, and I. Abe, "Condensation of lignin during heating of wood," *Wood Science and Technology*, vol. 24, no. 3, pp. 277–288, 1990.

[23] D. Fengel and G. Wegener, *Wood Chemistry Ultrastructure Reaction*, Kessel, Remagen, Germany, 2003.