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Laser cleaning of varnish from bog oak surface

Suzana Polić[1], Slavica Ristić[1], Bojana Radojković[2], Suzana Linić[3]

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INTRODUCTION

Today lasers have found numerous applications in science, industry, medicine, military and space programs, in many everyday life areas as well as in conservation studios [1]. Lasers can be used for surface cleaning; scribing, sintering, cutting, drilling, milling or marking. Laser interaction with materials is a very complex phenomenon [2-4]. It has been a subject of many studies, but there are still a lot of unknown phenomena [2-4]. Nanosecond and sub-nanosecond lasers open up a lot of possibilities for research in the field of laser-material interaction. Laser cleaning moved from research laboratories to commercial production, and then to the restoration and conservation field.

Laser treatment of different materials for conservation purposes such as wood, metals, and ceramics objects of cultural and historic value has increasing significantly in the last decade [5-13]. Each of these materials shows specific phenomena and gives different results in interaction with the Nd-YAG laser. Therefore it is very important to know the characteristics of the material and laser to choose the appropriate parameters of interaction.

A number of laser cleaning examples applied to wooden material available in the literature. The efficiency of the laser-material interaction depends on several parameters that are related to material properties of the substrate and the coating, and laser parameters such as wavelength, power density, and repetition rate. Laser cleaning should be used with good control methodologies [5].

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Wood is a natural product used by societies throughout the ages for its aesthetics and physical properties. It is rigid but can be shaped with temperature, moisture, and mechanical methods. It has a good strength to weight ratio and impact resistance. The primary factor affecting the results of using laser wood processing technology is the density and the uniformity of its density. Generally, these processes include laser drilling, laser cutting, laser grooving, laser engraving and laser marking or scribing. In paper [14] the features and the performances given by a 5W of nominal power Q-switched diode-pumped frequency-doubled Nd:YAG green laser in the engraving of different kind of woods are discussed.

Laser treatment of wood leads to some degradation of wood compounds. When wood absorbs the laser energy, it converts optical energy into molecular vibrations (heat). It leads to rapid decomposition and combustion, material in the affected zones is ablated away into vapor and fine particles. The material just outside of the laser's spot or path is heat affected zone or HAZ. Laser power had significant effects on color changes of a wood surface. The lightness decreased after laser treatment and it decreased with an increase of laser power. From the literature, there are still many areas to be studied to improve laser wood processing [15-17].

Bog oak is a type of wood (morta, ebony wood, black wood or abonos wood) that ranges in age from a few hundred to a few thousand years. Bog-wood is a naturally stained hardwood that is created from the trees that have been lying in lakes, rivers, and bogs for millennia. Black color of bog-oak is the result of chemical interaction of tan stuff in the wood and iron in water [18]. Water in the environment in which bog-oak is formed provides unfavorable conditions for the development of microorganisms and fungi that would decompose the wood. Deposition of minerals from the water ensures conservation and durability of wood structural elements. Bog oak has exceptional strength; it cannot be cut with regular tools. The color of the wood, which may vary from golden brown to ebony with a platinum sheen, is shaped by natural conditions that include variations in the water level, soil composition, and the acidity of the water (fig.1a). After bog oak has been extracted and dried, it is often used in the production of luxury furniture, jewelers, pipe, walking sticks, sculptures and various decorative objects. Items made of bog oak are usually varnished.

Oak god is a tree of high density and difficult to process, so lasers are used today instead of the classic tools. Lasers are used for cutting, surface processing, engraving and cleaning of unwanted layers. As it is stated in paper [13], the average value of density of bog-oak in the absolutely dry condition is 0.704 g/cm3, and is 15.8 % higher than that of the wood density in absolutely dry condition of recent oak. The average value of ultimate strength in static bending for bog-oak wood was 101.3 MPa, which is 10.8 % higher than the ultimate strength in static bending of recent oak wood.

Many items of the cultural and historical heritage were made of bog oak with different varnish coatings. Their cleaning is very important in the process of their conservation.

This paper presents the results of testing the ability of a laser to remove varnish on the surface of a sample composed of pieces of bog oak of different ages (Fig.1b). The laser cleaning tests were carried out with a Q-switched Nd:YAG system.

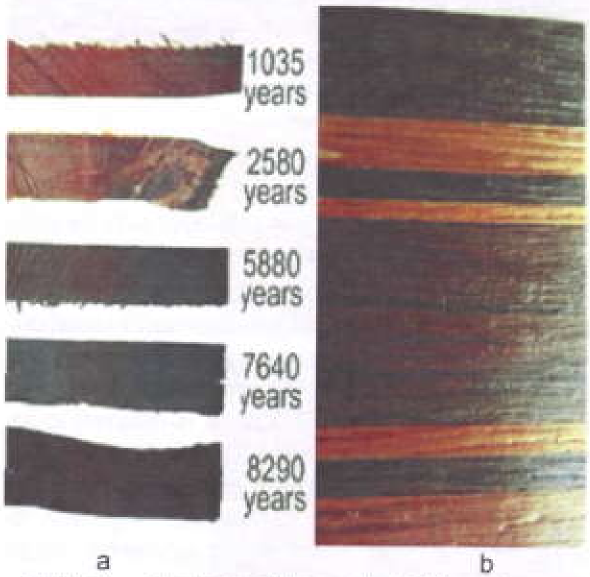

Figure 1 – a) pieces of bog oak of different ages [16], b) sample compose of different bog oak used in experiments

1. EXPERIMENTS

The experiments were performed using Nd: YAG laser, Thunder Art Laser, a product of Quanta System. The laser operates in the Q-switch mode with three λ: 1064 nm, 532 nm, and 355 nm. The duration of a pulse was τ = 8 ns. The repetition rate was fl = 1 - 20 Hz. The maximum energy of the laser beam, for λ = 1064 nm, was E = 510 mJ. The laser beam was focused by a lens with 150 mm focal length. The tested sample was positioned in front of the lens focus. A dry cleaning method was used. The experiment was performed in atmospheric conditions. The laser pulses were focused on the surface by a plano-convex spherical lens.

Nd:YAG laser is used in experiments because it has ns pulse, three wavelengths and low absorption in wood (fig 2) [19]. It is known that polymers are ablated very well with the different UV lasers, but ablation can occur at other wavelengths as well.

In order to calculate the various fluence values, the spot size was measured on blank indigo paper.

The test sample is a tile 65×45×5 mm, obtained by glued pieces of different ages bog oak. A thin layer of acrylic varnish is applied on the surface of the tile. Bog oak samples taken from the bottom of the Volga were obtained courtesy of the Museum "House of God Oak" Kozmodemyansk (Музей «Дом морёного дуба» Козьмодемьянск).

The bog oak has been built into some of the most important cultural heritage sites in Russia, such as Muranovo, today the Tytchev Museum, Tsarskoye Selo - Catherine Palace, Ostankino Palace, The Kuskovo Memorial Estate. It was used for marquetry in representative elegant parquets of halls, in compositions that were characteristic of the late Baroque and later, Classicism, and according to the projects of famous architects of Tsarist Russia [20].

The laser parameters used for cleaning are presented in Table 1.

Table 1 - Experimental conditions

Zone No.	λ (nm)	Φ (J/cm^2)	t(s)	Zone No.	λ (nm)	Φ (J/cm^2)	t(s)
1	1064	8.4	1	15	1064	6.4	1
2	1064	7.6	1	16	1064	6.4	5
3	1064	5.5	1	17	1064	6.4	10
4	1064	3.3	1	18	1064	6.4	30
5	532	3.3	1	19	1064	2.1	1
6	355	1.5	1	20	1064	2.1	5
7	355	1.5	1	21	1064	2.1	30
8	355	1.5	5	22	1064	1.7	1
9	355	1.5	10	23	1064	1.7	5
10	355	1.5	30	24	1064	1.7	10
11	532	3.3	1	25	1064	0.9	5
12	532	3.3	5				
13	532	3.3	10				
14	532	3.3	30				

The surface was examined before and after the cleaning. USB optical microscope is used for morphological analysis after laser treatments. SpectraWiz spectrometer was used for color changes investigation. The used colorimeter shows the results in the CIE L* a * b * (or CIELAB) space.

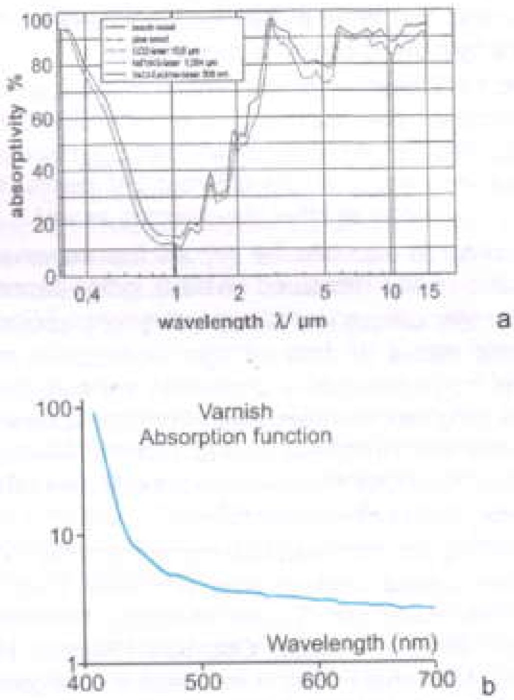

Figure 2 - Spectral absorptivity of: a) wood [19], and b) varnish [19].

2. RESULTS AND DISCUSSION

The laser beam can interact with a transparent or opaque solid surface producing various effects, depending on the laser and material parameters [1]. Laser ablation is a process consisting of optical, photo thermal, photo chemical, photo acoustic and photo mechanical phenomena, in which the absorption of a large number of photons heats the material and performs surface modification. The exact nature of the material ablation by laser irradiation depends on the used material and laser processing parameters [1–6]. For successful ablation, it is necessary that the material that is removing has a different, higher absorption coefficient compared to the material that is the substrate. According to fig 2 wood and varnish have similar spectral absorptivity, which is not favorable for the selective ablation layer of varnish on the surface.

The analysis of the laser impact effects on varnished bog oak samples shows that, in most cases, irreversible microscopic and macroscopic changes have occurred on the varnish or in the wood material. The applied fluences in the experiments were close to the damage threshold for the wood. The macroscopic analysis of the tested sample (Fig. 3) shows that the applied laser fluences caused visible changes.

Laser ablation is the physical mechanism behind laser varnish removal. The physical parameters of the laser irradiation, like wavelength, fluence, pulse width, repetition rate, are responsible for the characteristic phenomena causing material removal (Fig.3).

Figure 3 - Laser irradiated zones on sample

The advantages of the laser varnish cleaning are possibility of high accuracy, spatial and temporal control, an immediate change of laser parameters, material selectivity, and ecologically friendly characteristics.

The reflectance with and without varnish to establish the absorption, scattering, transmittance, and reflectance spectra of the varnish layer can be estimated by Kubelka-Munk two-constant theory [21].

A study performed by Zafiropulos et al. [22] made some important findings on varnish irradiation. It was experimentally demonstrated that when the fluence increases the efficiency also increases until a maximum is achieved. This point is referred to as the saturation point in light absorption. At higher fluence irradiation is transformed into thermal energy. Inhomogeneous depth of the varnish (e.g. due to cracks) can decrease the cleaning efficiency, visual impression after the laser treatment.

Figure 3 shows the results of the laser removal of varnish on bog oak plates (zones 1-25).

Figures 4, 5 and Figures 6 show the results of laser ablation recorded with USB optical microscopy with 45 and 135 magnification.

The results presented in this paper have confirmed certain statements in the literature [17,22] that the varnish is best removed with laser pulses in the ultraviolet part of the spectrum. Cleaning varnish from the surface of bog oak is not study enough. With low fluences and 20 laser pulses in one second (Fig 4a, zone 4 and 3), partial melting and ablation occur, and with higher fluences and some number of pulses, the wooden substrate is damaged (fig 4b, zone 1 and 2).

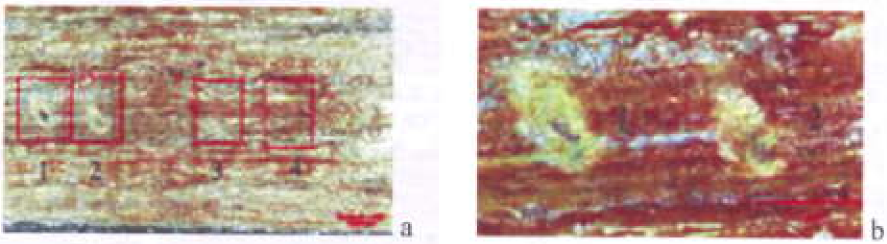

Figure 4 - Laser treated zones on part of lighter ebony (zones 1-4)

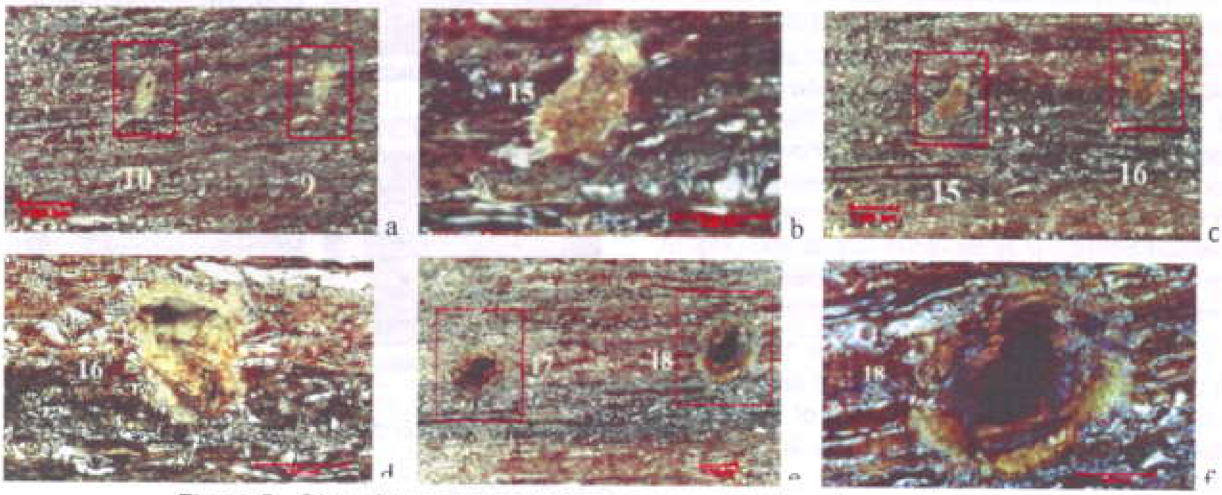

Figure 5 - Some Laser treated zones on part of darker ebony with 2 × 1 mm

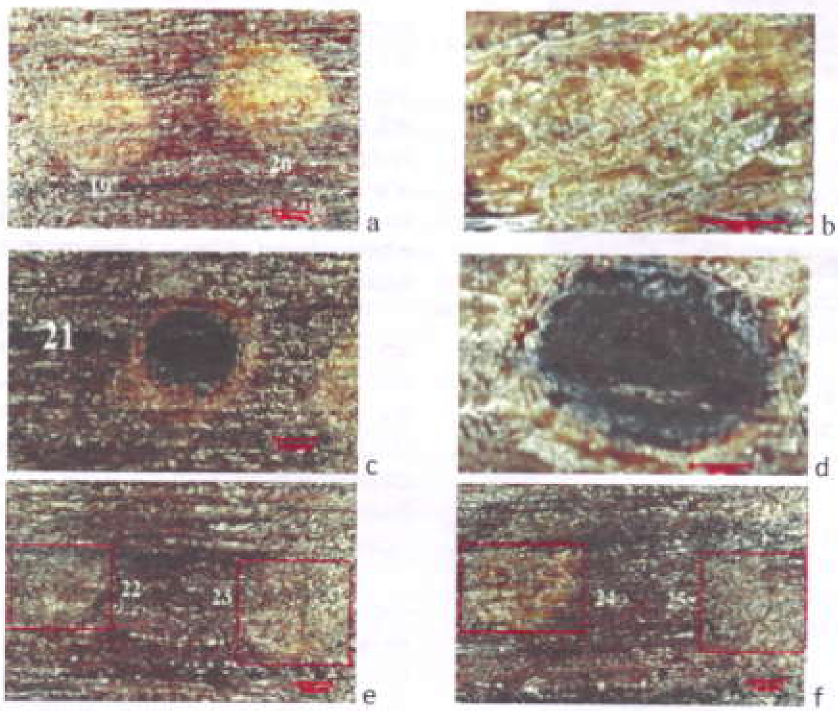

Figure 6 - Some laser treated zones on part of darker ebony with enlarged laser spot

Zones 9 and 10 (Fig. 5a) were treated with blue laser light (λ=355nm) with low fluence (Tab.1), but with a higher number of pulses. The area of the zones in which the varnish has been removed is wider in relation to zones 1 and 2 in Figure 4a.

Figures 5b-5f shows the influence of the number of pulses on the results of the laser material interaction. For the same fluence 6.4 J/cm2, with an increase in the number of pulses from 20 to 600, (1 to 30 s) the varnish has partially melted and removed (Fig. 5c), then the wood substrate is damaged (Fig. 5e, zone 17 and Fig. 5f, zone 18).

Zones 19-21 were irradiated with fluence of 2.1 J/cm2. The number of pulses increased: 20 (Fig. 6, zone 19), 100 (Fig. 6a, zone 20) and 600 (Fig. 6c and 6d, zone 21). The better results for safe varnish removal were obtained for this fluence (2.1 J/cm^2 and 100 pulses (zone 20). Increasing the number of pulses wooden base was damaged and a hole was made (fig.6c and 6d). Zones 22-24 were irradiated with lower fluence 1.7 J/cm2. The number of pulses increased from 20 (Fig. 6e, zone 22), to 300 (Fig. 6f, zone 24). The analysis shows low efficiency of varnish removal from the surface of the bog oak.

Figure 7 shows a picture of zone 16 recorded with optical zoom 155x. In this zone, a layer of varnish has been partially removed. Part of the varnish melted and hardened again, forming a thin mesh structure composed of varnish threads.

Figure 7 - Zoomed image of zone 16 with re-solidified varnish layer

Laser wood treatments often induce color changes. Figure 8 shows that in the zones of laser treatement there is a change in color from gray to gray-brown.

These changes are influenced by the laser power. Changes in the color, the chemical and morphology structure of the modified wood are mainly caused by thermal processes in wood.

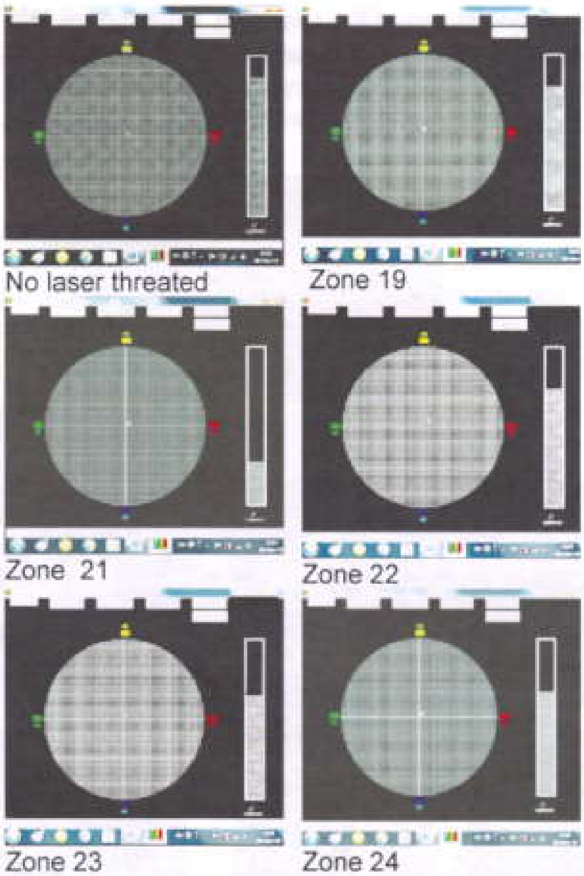

Figure 8 - CIELAB diagrams for laser treated zones

CONCLUSION

Due to the difficulties in the varnish cleaning from wood surface with common procedures based on mechanical or solvent systems, laser cleaning was tested. The laser tests, performed under different conditions, allowed finding suitable parameters to reduce the varnish layer and to remove the surface dirt deposits without damaging the wood surface. The effectiveness of the Nd:YAG laser cleaning was explored utilizing video-microscope observation and reflectance spectrophotometry.

The results of Nd:YAG laser application in varnish cleaning, presented in this paper, have confirmed that the varnish is best removed with laser pulses in the ultraviolet part of the spectrum. Nd:YAG laser (1024, 532 and 355 nm) is not enough efficient for cleaning varnish from the surface of bog oak. With low fluences, partial melting and ablation occur, and with higher fluences, the wooden substrate is damaged.

A small number of laser cleaning examples applied to wooden material are available in the open literature and every new experience could be useful for further investigation, especially when laser is used for removing varnish from surfaces of precious objects made of bog oak.

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ABSTRACT

LASER CLEANING OF VARNISH FROM BOG OAK SURFACE

The removal of varnish is a very challenging task in the conservation of wooden artifacts. The results of experiments performed to investigate the suitability of lasers for cleaning aged varnish from bog oak wood (ebony) are presented in this paper. Optimal laser parameters for safe and efficient varnish ablation were determined in order to preserve the integrity of the original wooden substrate during the cleaning process. The ablation threshold for varnish and wood damage threshold was examined using Nd:YAG laser (1064, 532, and 355 nm) emitting pulses of nanosecond (8 ns) duration. Results of induced varnish removal and other morphological alterations to the wood surface were investigated by optical microscopy and colorimetry.

Keywords: *laser, Nd:YAG, semiconductor, ebony, ablation, varnish, laser cleaning.*