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THE EFFECT OF A LASER BEAM WAVELENGTH ON ACCURACY OF SURFACE MEASUREMENT OF UNEVENNESS OF BEECHWOOD BY LASER BEAM

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ABSTRACT

The laser wavelength modifications used in a laserprofilometer device (LPM) to measure the unevenness of machined surfaces are described in the paper. The aim of the paper is to find the optimum wavelength of the laser with regard to the accuracy of measuring the wood surface roughness and to prove the relationship between the accuracy of measuring and the wavelength of the light emitted by the laser modules. The results of the measurements during which a source of red light (wavelength $\lambda = 635$nm), green light ($\lambda = 520$nm) and blue light ($\lambda = 450$nm) and beech wood surface with humidity were tested in a set of LPM laser profilometer. The results of the research showed an increase in the sensitivity of the surface roughness measurement by 60% using a blue laser beam with a $\lambda = 450$nm wavelength compared to standard red laser lamps with $\lambda = 635$nm wavelengths.

Key words: roughness, surface profile, measurement, waviness, laser profilometer, LPM.

INTRODUCTION

The surface of the workpieces made of wood and wood materials carries the marks of machining (sawing, milling, grinding) as well as marks resulting from is own structure, material structure and material properties reacting to the change in external conditions (Figure 1). Surface quality assessment can then be broken down according to the most important properties and frequent errors of geometric, optical, structural and visual errors (WHITEHOUSE 1994).

The current period of industrial production is characterized by high requirements not only for accuracy but also reproducibility of production. Improved manufacturing precision is achieved a by clear interpretation of production documentation and strict adherence to standardized control procedures. ISO responds to these requirements by compiling a plan which, creates the structure of the necessary standards for the Geometrical Product Specifications (GPS) field and this specifies the corresponding normalized activities.

STN EN ISO 4287 - Surface Characteristics - Profile Method defines the terms, definitions and parameters of the surface. The standard is based on the surface profile assessment by the profile method, i.e. evaluates the surface profile, i.e., a line that results from the cut of a real surface defined by the cross-cut. In practice, it is customary to select a plane whose normal is parallel to the actual surface and has a suitable direction. A good direction is the one in which we find larger values of surface character parameters (cross section) (STN EN ISO 4287, 1999).

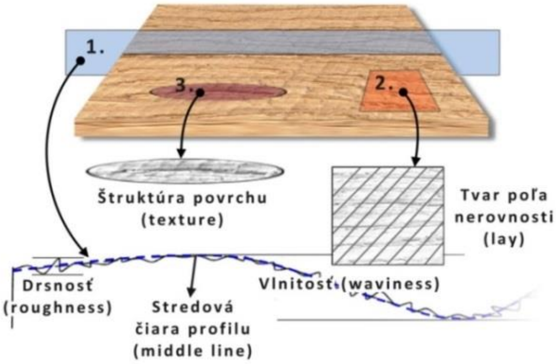

Fig. 1 Surface assessment. 1. Reduced plane - evaluation of primary profile, roughness profile and inequality profile, 2. Surface nature - shape and direction of the area of inequality, structure and surface errors.

The STN EN ISO 4288 standard follows STN EN ISO 4287 (STN EN ISO 4288, 2000), which defines the rules and procedures for surface profile assessment by the profile method.

Contact measurement devices are the most commonly used to control and measure of surface roughness, but recently they are beginning to assert more and more non-contact measurement equipment based on optical measurement principle. One of the new measuring instruments utilizing the optical method of measuring inequality using the profile method is the construction of LPM laser profilometers. The LPM profilemeters, their hardware and software parts, are based on the surface roughness measurement specifications by the profile method defined in STN EN ISO 4287.

In terms of the use of modern technologies in production processes, 3D scanning technologies are increasingly being promoted. These technologies are predominantly used to control products, surfaces, and evaluate their parameters, a reverse manufacturing process, quality control, wear-out measurements, and surface roughness. Manufacturers of these measuring devices using the non-contact optical profile geometry principle use the most commonly used source of laser light at the wavelength of 620–650nm. These wavelengths correspond to a spectrum of red light that is the most economical in production of laser diodes. Several scientific papers (Bargigia 2013, Lockwood 2016, Venturini 2017, Bekhta and Krystofiak 2016) have demonstrated Rayleigh's criterion, the benefit of changing the wavelength of the light used to precision and measurement sensitivity in the area of laser profilometry.

The aim of the article is to find the optimum wavelength of the laser source used in the laser profile meter (LPM) regarding the accuracy of measuring the roughness of the sawmill surface and to prove the correlation between the accuracy of measuring the surface roughness of the cut wood and the wavelength of the light emitted by the various laser modules.

DESIGN AND MEASUREMENT PRINCIPLE OF LPM

The horizontal adjustment of LPM (Fig. 2) consists of a supporting aluminum structure on which the power elements of the device are located. The support structure enables the vertical positioning of the profile head, which is necessary for the exact focus of the camera for the different body heights. The main part of the device is a profilemetric head consisting of a Marlin F131B firewire camera and laser diodes with a light source with a wavelength of 635nm and the power of 3mW. An additional part is a set of two micrometric Standa

8SMC1 sliding tables (Allied Vision 2015). The feed set allows a working motion in the XZ plane in the 100 mm range with a precision of 1 μm.

There is used the camera of German manufacturer Allied Vision Technologies, who has long been a leader among the leaders in this area. The Marlin F131B has a 2/3 "Cypress IBIS5 CMOS chip, with a maximum frame rate of 25fps, with a maximum resolution of 1280x1024 (Allied Vision, 2015). The camera has a 10 bit A/D converter and a glass filter and communicates over Firewire with a laser projects the line onto the material surface. The laser line is adjusted on the distance for which the camera's working distance is calibrated. LPM uses the triangulation principle of laser profilometry. The image of the laser line is under an angle by a digital camera. The cross-sectional profile is then evaluated from the scanned image. The cross section and hence the shape of the surface profile is determined by the laser line.

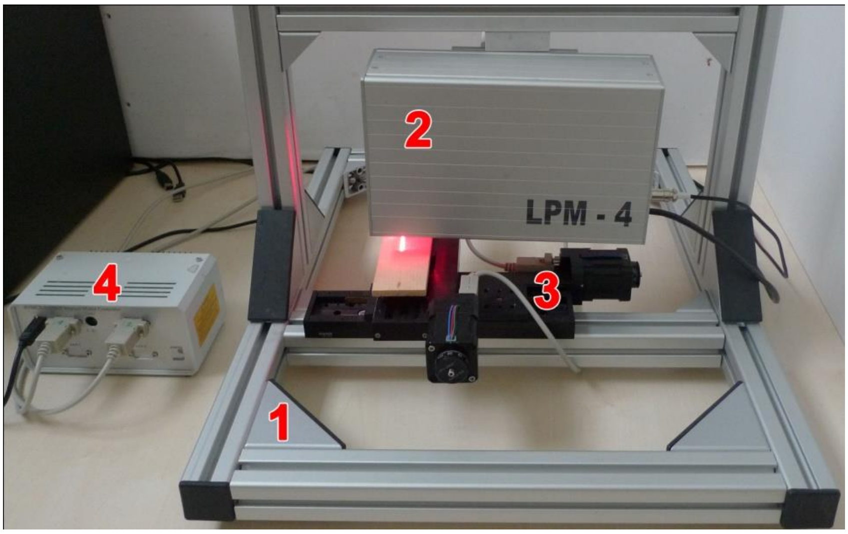

Fig. 2 The LPM-4 laser profile assembly: 1. A load-bearing structure allowing manual presetting of the working distance and fixing of the profile head and the set of sliding tables; 2. Profilemetric head; 3. XZ axis shifting assembly; 4. Work table shifting control unit.

Tab. 1 LPM unit parameters.

Type of LPM	Laser wavelength	Laser power	Working distance	Working range	Basic length	Evaluated length
60	650 nm	40 mW	100 mm	200 μm – 30 mm	60 mm	120 mm
4	450–660 nm	10 mW	20 mm	3 μm – 1000 μm	4 mm	90 mm

The principle of LPM measurement consists of three steps:

a) Image capture - the measured is placed object between the camera and the light source. In terms of measurement, the best solution is to use a black and white digital camera. The camera shall project an image of the illuminated object onto the light-sensitive chip placed in the camera through the lens. The light-sensitive chip contains a number of light-sensitive units (pixels). Each pixel senses the intensity of the light separately, while the light intensity carries information about the light transmittance of the object being measured, as well as the background (KMINIAK and GAFF 2015). The intensity of light in the pixels is then electronically processed, depending on the type of camera in 8-bit form, which represents 256 levels of light intensity. The result is an image composed of a set of pixels whose color is in the range of 0–256 levels of gray, depending on the light intensity of the pixels.

b) Image binarization - In the next process, the image is processed by the software programe. The light intensity threshold is determined, so all pixels that have a lower intensity level are assigned a black color and the other pixels white color. In principle, it distinguishes the object from the background, allowing maximum resolution of the measured object and background.

c) **Measurement calibration** - the result of image binarization is a set of white and black pixels representing the image of the object being measured and the background. So, we can see how many pixels represent the individual geometric parameters of the measured object. If we put the measured object between the camera and the light source whose geometric parameters we know, then we can assign the number of pixels to individual parameters. In this way, the pixel dimensions are defined in measured units, and we can assess geometric parameters of objects (KMINIAK and BANSKI 2017). However, it is necessary for the measured objects to be located at the same distance from the camera (to maintain the measuring plane) (KVANT 2014).

METHODOLOGY

Measurement of surface roughness was performed on the LPM 4 with 3 laser light sources with different wavelengths. The test sample material was tangential beech (*Fagus silvatica*) cuts with thickness h = 20mm, width w = 50mm and length l = 1000mm. When selecting samples, an emphasis was placed on samples that contained as few knots as possible and had the same increase in annual rings. The samples were cut in the tangential directional plane. The wood was dried to 12 ± 1% moisture. Cutting with 5 mm saw blades were used, cutting speed $v_c = 62{,}3$ m.s^{-1} and feed rate $v_f = 10$ m·min^{-1}. The wood was cut in the longitudinal direction. The sampling was carried out by means of a saw blade which a blade made of high-speed steel.

Parameters of a high-speed steel saw blade:

Diameter of the saw blade:	400 mm
Saw blade thickness:	2,5 mm
Cutting width:	3,6 mm
Number of teeth:	32
Rotation speed:	3800 [min-1]
Manufacturer:	Pilana
Geometry of sawtooth	$\alpha = 15°$, $\beta = 50°$, $\gamma = 25°$

The reference material of the experiment was the aluminum standard (Figure 3b) with the surface roughness value of Ra = 10μm. This standard was selected on the basis of preliminary measurements of unevenness of the beech sample surface.

a) b)

Fig. 3 Materials samples - a) beech, b) aluminum standard.

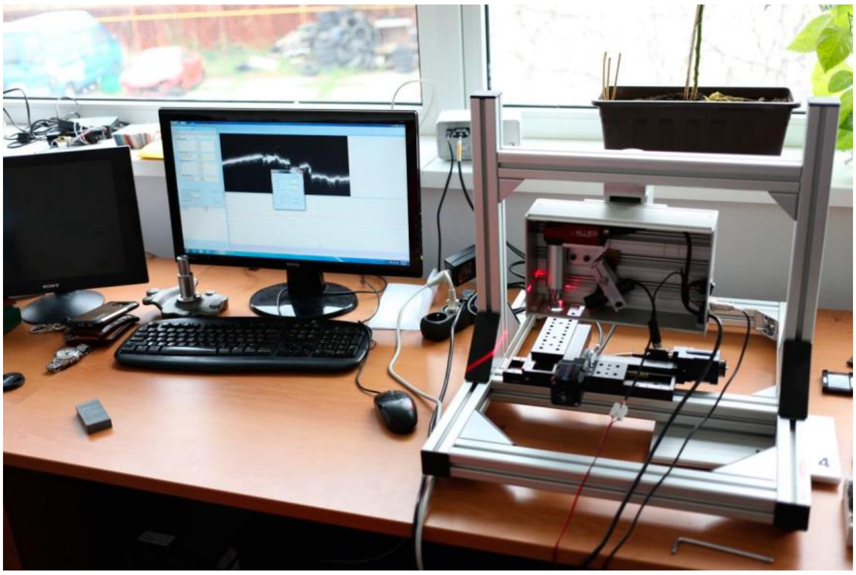

Fig. 4 Laser profilemeter during experimental measurements ready for exchange of the laser light source.

In the scope of the experiment, three types of laser diodes with different color (wavelength) of emitted light were tested in the LPM 4 laser profilometer. The open structure of the laser profilemeter is shown in figure 4. The LPM's internal construction allowed easy exchange of three laser diodes during the experiments. For each source, the system had to be recalibrated using calibration measurements. Measurement of surface roughness began with red laser light, followed by green laser light and eventually we installed a blue laser light source into the LPM.

Range of modified wavelengths of laser light sources:

- measurements with red light λ = 635nm,
- measurements with green light λ = 520nm,
- measurements with blue light λ = 450nm.

Each sample measurements were represented by 20 measured values obtained by Long Scan in LPM View. We then pasted these values into Microsoft Excel, where we subjected them to a statistical analysis. We were interested in the arithmetic mean, the standard deviation and the variance of the roughness parameter Ra.

Fig. 5 Long scan configuration.

The scan was carried out over a length of 4450 µm, one of the measurements was made every 220 µm, producing 20 values together. In the resulting parameters, we focused on the roughness value Ra.

ANALYSIS OF RESULTS

Measured values of height elevation surface roughness for beech samples and comparative aluminum standard Ra = 10µm using three different lasers were statistically processed. The results of the measurements on the standard and the surface of the beech samples by the individual factors evaluated by the altitude inequality Ra surface and the colors of the used laser lights in the form of the arithmetic mean, standard deviation and variance are in tab. 2–3. In the case of the aluminum standard with roughness Ra = 10µm, also the percentage deviation from the graph compared to the standard roughness is mentioned.

The most objective measurement was the measurement of the aluminum sample representing the roughness standard with Ra = 10µm (Figure 6). Due to the uniform processing of the sample and the specified roughness constant we were able to demonstrate a significant increase in the accuracy of the measured values using shorter wavelength laser light. While in the red light the deviation from the norm was up to 12.7%, the green light was accurate with a 3.3% deviation and with the blue laser the measurement, based on 20 measured values, went up to a thousandth percent deviation (tab. 2).

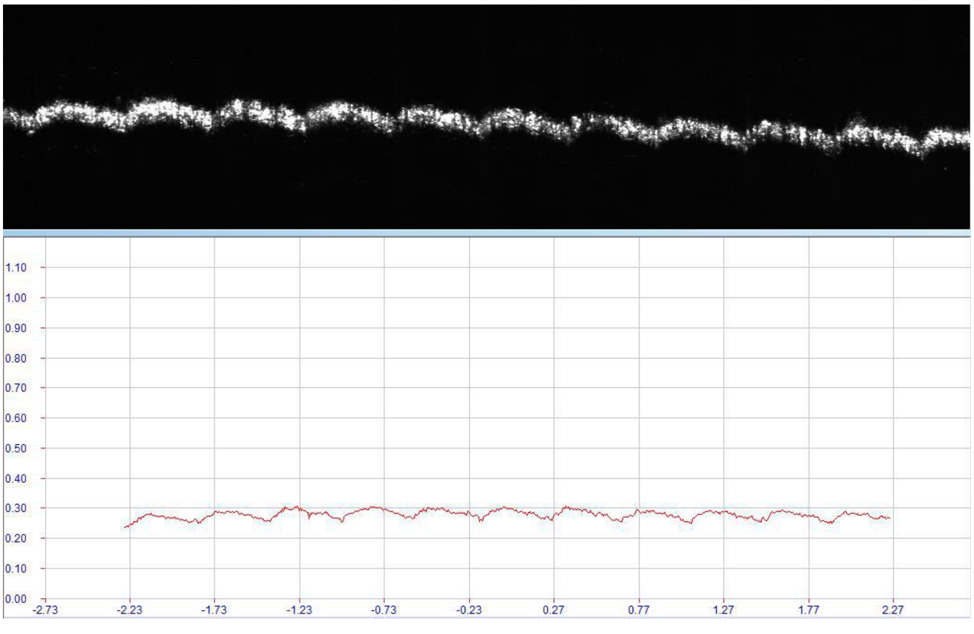

Fig. 6 Measurement of the aluminum sample structure in LPM View.

Tab. 2 The calculated statistical data for planed aluminum.

	Planed aluminium (R_a = 10 µm)		
	λ = 635nm	**λ = 520nm**	**λ = 450nm**
Arithmetic mean	0,0112707mm	0,01033mm	0,00999mm
Standard deviation	0,000542903mm	0,000384mm	0,00038mm
Spread	2,94744E-07	1,47E-07	1,45E-07
Deviation from the norm	12,707%	3,3%	0,001%

Tab. 3 The calculate statistical data for the beech wood sample.

	Cutting beech		
	λ = 635nm	λ = 520nm	λ = 450nm
Arithmetic mean	0,01129365mm	0,011034mm	0,009975mm
Standard deviation	0,003339229mm	0,003833mm	0,003474mm
Spread	1,11504E-05	1,47E-05	1,21E-05

Manufacturers of various measuring instruments, using either distance or surface roughness, prefer a red light spectrum at the wavelengths of 620–670nm at the laser light source. The reason for the most common use is the lower cost of the laser diode compared to green and a blue laser diode.

Several scientific papers (BARGIGIA 2013, LOCKWOOD 2016, VENTURINI 2017, VAZQUEZ *et al*. 2011, ORLOWSKI 2009) have highlighted the benefits of using different wavelengths when measuring different materials. Various authors have agreed that in terms of cost and accuracy of measurement in measuring the surface roughness of different materials, the most suitable is a green laser light with a wavelength of 520nm. Since the measurements in these scientific works have been carried out on predominantly homogeneous materials (metal, plastic, rubber), we have decided to test the benefits of different wavelengths on an inhomogeneous and more diffuse surface such as natural wood.

By experimental measurement, we succeeded in demonstrating the validity of Rayleigh's criterion, which says the resolution of the optical system increases when by reducing the value of the wavelength of the emitted light decreases (LOCKWOOD 2016, RUDDICK *et al*. 1993). The Rayleigh criterion allows the calculation of the smallest resolvable distance of two points:

$$a = 1{,}22 * \frac{\lambda}{D} = 0{,}61 * \frac{\lambda}{R}$$

Where λ is the wavelength of the used light, D represents the numerical aperture of the lens, and the number 1,22 represents the diffractive constant. The lens enlarges this dimension and projects it onto the camera's photosensitive chip (Allied Vision, 2015). The question was whether the variance of the measurement values based on the nature of the measured surface of the machined wood will be preserved at the smallest wavelength of the light (in our case it was blue light of 450nm) and (according to the above mentioned criterion) besides the greatest sensitivity of the measurement. By experimental measurements, we found out that it is preferable to use a laser beam with a lower wavelength compared to the original source of laser light with a red color of 635 nm. By changing the wavelength of the used laser light source, the sensitivity of the profilometer increased from 3μm to 1.6μm using the green light (520nm) and to 1.2μm using the blue light of 450nm wavelength.

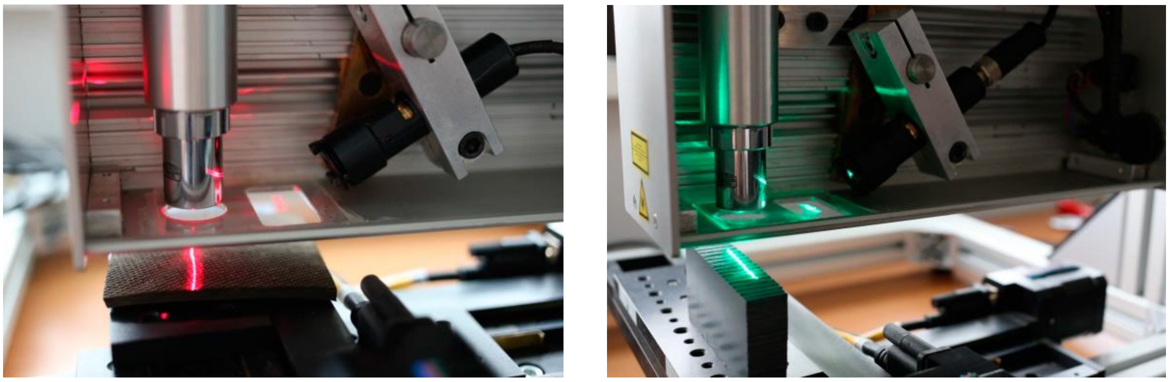

Fig. 7 Measurement with red light (a) of wavelength λ = 635nm, measurement with green (b) wavelength λ = 520nm.

Fig. 8 Measurement with blue light of λ = 450nm.

Calculation of the percentages of the sensitivity of the LPM4 laser profilometer:
- using green light:

$$x = 100 - \frac{R_{Z-min}}{R_{C-min}} * 100\% = \frac{1{,}6\mu m}{3{,}0\mu m} * 100\% = 46{,}66\%$$

- using blue light:

$$x = 100 - \frac{R_{M-min}}{R_{C-min}} * 100\% = \frac{1{,}2\mu m}{3{,}0\mu m} * 100\% = 60\%$$

CONCLUSION

One of the main benefits of this work is to demonstrate the improvement on laser projection accuracy by optimizing the wavelength of the used laser. Experimentally, the Rayleigh criterion was shown valid to increase the optical resolution of the light through the decrease of the wavelength value of the emitted light.

Laser profilometers are an optical non-contact method for measuring and evaluating profile parameters of surface roughness. The optical method also allows you to measure geometric parameters of objects that are difficult or impossible to measure by standard measurement methods. The method represents much faster, more accurate and especially more reliable solution compared to manual measurement systems. As a result of the experimental measurements, it is preferable to use a blue light with a wavelength of 450 nm as the laser light source compared to a standard 635 nm red light available in the standard and economically available version.

The experiments confirmed the higher accuracy and sensitivity with the blue light compared to the red light. When red light was used, the minimum height of the measurable inequality was set at 3 µm. Using blue light, it was possible to reduce the boundary of measurable height of unevenness to 1 µm. We consider this enhancement of the LPM 4 laser profilometer to be very important and desirable, to improve woodworking technology that creates surfaces with significantly lower surface roughness.

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