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ORIGINAL ARTICLE

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Evaluation of surface smoothness by laser displacement sensor 1: effect of wood species

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Abstract The best methods for determining surface roughness in an industrial environment are of the noncontact variety, with reproduction of the profile. The objective of this work was to compare the roughness profile obtained by a contact stylus with a commercial laser displacement sensor (LDS). Measurements were done using 15 wood species with different densities and colors, based on which special triangle profiles were prepared. The accuracy of the laser sensor was examined by statistical analysis of roughness parameters measured from the profiles. Experimental results show that LDS profiles were imitated correctly. However, LDS accuracy depends on the scanned wood properties (density and color), installation position of the sensor, and profile shape. It was found that evaluation of dark and high-density wooden surfaces was imperfect.

Key words Wood surface roughness · Laser displacement sensor · Wood density · Color of wood

Introduction

Technical progress in the wood industry has been rapid in recent times. New technologies require modern sensors for accuracy and real-time measurement of process parameters and product quality.[1] Surface smoothness is one of the most important parameters characterizing the wood machining process and its conditions. Moreover, in recent years, interest in production of high-quality surfaces has increased for several reasons. Quality assurance during production and testing must be aligned with customer-oriented quality criteria.[2] Consumer products (e.g., furniture, doors, flooring) generally exert an effect on customers by their outer appearance. The decision to buy a product is more influenced by aesthetics than by functional factors. Unfortunately, the anatomical complexity of wood and wood-based materials, wood density, moisture content, fiber direction, kinematics of the cutting process, machine condition, and other factors make the wood surface complex. Consequently, it is difficult to assess wood roughness.

Several methods are used in the wood industry to test product smoothness.[2,3] Each technique has specific advantages and disadvantages. The most popular method, human inspection, is not acceptable because such classification is subjective, depends on personnel knowledge and experience, and is affected by worker fatigue, among other factors.[3] Destructive methods are expensive, are time-consuming, and cannot be used for on-line quality monitoring. Use of pneumatic,[4] photographic,[5] or reflection[6] methods is limited because they do not reproduce the real surface profile. The contact and the low speed of the most accurate stylus method are not acceptable for production applications,[3] although the stylus method is commonly used in laboratories and for off-line roughness measurements of engineered surfaces.

The best method for determining surface smoothness in an industrial environment is of the noncontact variety with reproduction of the profile. Among the methods are various optical profilometers (mostly laser-based),[7] microscopes, image analyzers,[8] imaging spectrographs,[9] interferometers,[10] fiberoptic transducers,[11] white light speckles,[12] laser scatters,[13] and optical light sectioning systems.[14]

It is necessary to develop surface roughness measurement methods that are insensitive to possible changes in the workpiece condition, accurate, and suitable for use in an industrial environment. The objective of this work was to investigate the accuracy of a laser sensor for measuring the

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Part of this work was presented at the 50th Annual Meeting of the Japan Wood Research Society, Kyoto, April 2000; and at the 51st Annual Meeting of the Japan Wood Research Society, Tokyo, April 2001 smoothness of various wooden surfaces by comparing an optical-laser sensor with a stylus.

Materials and methods

Displacement sensors

The laser displacement sensor (LDS) examined here uses a triangulation measurement approach. Laser light emitted by a semiconductor laser diode passes through a transmitter lens and is focused on the target. Some of the light energy reflects from the target and, after passing through a receiver lens, is focused on a position-sensitive detector (PSD). The detector uses the distribution of the entire beam spot entering the light-receiving element to determine the beam spot center of gravity and identifies it as the target position.[15] If the LDS's distance to the measured surface changes, the position of the reflected spot on the detector changes proportionally. This process can be correlated with the smoothness of the measured surface. When the sensor is moved over the investigated plane, a linear profile can be observed. The laser light wavelength emitted by the diode was 670 nm, and the incidence and reflectance angles of laser light were 0° and 22°, respectively. The laser spot on the wood surface was approximately 80 μm in diameter, although this value varied depending on the surface conditions. A laser displacement sensor can monitor intensity simultaneously with the displacement measurement. Intensity is a relative parameter, without units, characterizing the laser light quantity reflected from the measured surface into a detector. It changes in the range 1–50 000 depending on the surface properties, especially the surface's color. For dark surfaces the intensity has a low value, and for bright surfaces it is much higher.

In our experiment, an LDS was compared with a stylus profilometer. The stylus technique was chosen because it is well known and is an accurate, popular method. The stylus measurement is not perfect, however. Its main disadvantages are the tip dimension,[16] shape of the tip, flank angle,[17] excessive tip weight or pressure,[13] and tilting of the stylus holder arm.[18] All these factors distort the scanned profiles and reduce the accuracy of the measurement.

The stylus sensor used in the experiment had a specially prepared steel tip with an angle of 29° and a tip radius of 10 μm. This stylus geometry was chosen to minimize profile misrepresentation on steep profiles (Fig. 1). When a traditional (Taylor type) stylus penetrates a deep surface irregularity, the contact region between surface and stylus is shifted from the peak to the flank of the stylus, thereby giving false readings. A reliable measurement requires that all sensors be moved on exactly the same trajectory. To minimize experimental error, the installation positions of all sensors were carefully controlled.

Setup

Figure 2 shows the setup of the experiment. A computer with a General Purpose Interface Bus (GPIB) interface and programmable logical controller (PLC) module controls the position and speed of a numerically controlled x–z cross table. The laser displacement meter settings were controlled through an RS-232 serial port. Two LDSs (Keyence LC-2450) were installed on the vertical support of the cross table. For the first laser sensor the angle between the light triangle and movement direction was 90° (perpendicular position); and for the second laser sensor this angle was 0° (parallel position). The light triangle is defined as a figure where one of the triangle's sides is the path of laser light emitted into the surface, and the second side is the path of laser light reflected into the position detector. Figure 3 shows the mounting positions of both LDSs.

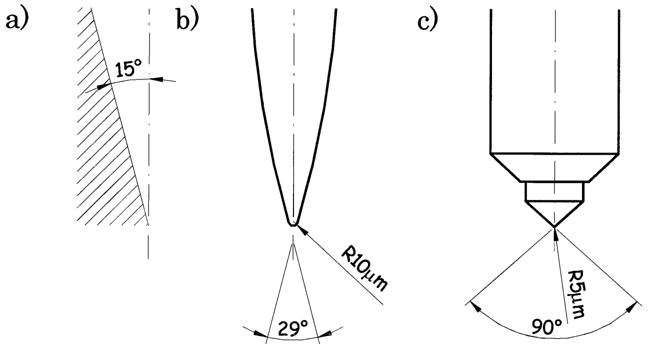

Fig. 1. Traditional and experimental stylus designs. **a** Maximum profile slope. **b** Stylus tip used in the experiment. **c** Popular Taylor-type stylus

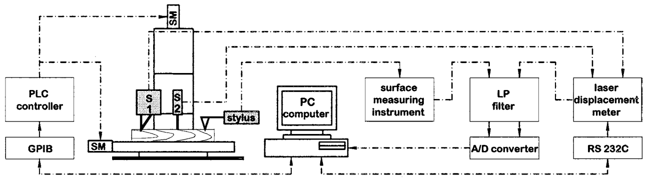

Fig. 2. Experimental setup. *S1*, laser displacement sensor (LDS) installed parallel to the movement direction; *S2*, LDS installed perpendicular to the movement direction; *SM*, stepper motor; *PC*, personal computer; *LP*, low pass; *A/D*, analog/digital; *GPIB*, General Purpose Interface Bus

The experimental data generated by the sensors were acquired by a 12-bit analog/digital (A/D) converter card (Quatech DAQ-1202), and after preanalysis the data were stored in the computer's memory. For the experiment, custom software was prepared using MS Visual Basic. The program was also able to supervise the cross table and laser displacement controllers and to calculate surface roughness descriptors.

Workpiece

A total of 15 specimens made from wood species with various colors and densities (Table 1) were the workpieces of the experiment. The wood samples were without defects and were conditioned to approximately 11% moisture content. Blocks were cut by a computer numerical control (CNC) router machine, and triangle profiles (stairway shaped, as shown in Fig. 3) with different geometries

Table 1. Wood species ($n = 15$) investigated in the experiment

English name	Latin name	Density (g/cm^3)	Color[a]
Yellow meranti	*Shorea* sp.	0.36	9180
Sugi	*Cryptomeria japonica*	0.42	8086
Okume	*Aucoumea klaineana* Pierre.	0.46	7515
Western hemlock	*Tsuga heterophylla* Sarg.	0.47	10605
Ash	*Fraxinus* sp.	0.50	7377
Sassafras	*Sassafras albidum*	0.55	7446
Beech	*Fagus crenata* Carr.	0.63	9407
Japanese oak	*Quercus mongolica*	0.68	7121
Keruing	*Combretocarpus rotundatus*	0.68	7516
Sakura	*Prunus jamaskura sieb* Makino	0.70	7863
Matoa	*Pometia* sp.	0.71	8133
Hornbeam	*Carpinus* sp.	0.72	9732
Keyaki	*Zelkova serrata* Makino	0.76	8559
Kempas	*Coompasia excelsa*	0.87	5234
Ebony	*Diospyros* sp.	0.98	1048

[a] Average intensity of light reflected from the wood surface

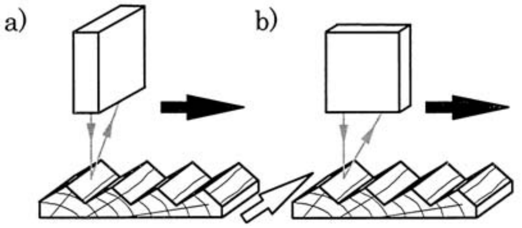

Fig. 3. Position of the laser head referenced to the movement direction. **a** Perpendicular. **b** Parallel. *Black arrows* indicate a moving course; *white arrow* indicates wood fiber direction

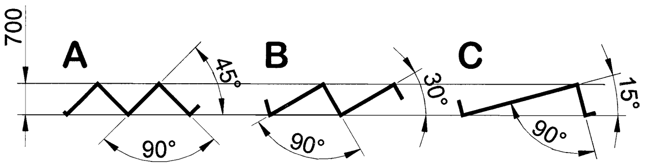

Fig. 4. Set of triangular profiles investigated during the experiment

were prepared. The triangle profiles are common profiles generated during wood processing. After cutting wood by a band saw or circular saw, the surface is composed of triangles. The triangular form depends on the saw geometry, processing conditions, and wood properties. Profiles prepared for the experiment were of varying steepness (profiles A, B, and C with vertex angles of 45°, 30°, and 15°, respectively) and a height of 0.7 mm (Fig. 4). The triangle peak's angle was 90°. To ensure faultless profile geometry, the cutting speed of the router machine was limited to 5.25 m/s with a feed speed of 0.5 m/min. The wood fiber direction was parallel to the feed direction. After cutting, the profile quality of all samples was verified by microscopy. Only properly produced triangle profiles were chosen for the next evaluation.

Experimental procedure

All profiles were scanned along a straight line three times: by a laser sensor positioned parallel to the movement direction, by a laser sensor positioned perpendicular to the movement direction, and by a stylus. The sensor movement speed was 0.3 mm/s, and the sampling length was 8 mm. The profile data were collected at a rate of 128 sample points per millimeter. Laser-scanned profile lines were compared to the profile lines scanned by the stylus and the theoretical ones (an ideal image of the triangle form). Surface roughness parameters [R_a, R_y, R_z, kurtosis (Kt), skewness (Sk)], the average intensity of the laser light reflected from the wood surface, the average error (Eq. 1), and the linear regression coefficients (slope and r^2) for the corresponding values of theoretical, stylus, and laser profile points obtained from profiles were calculated and analyzed.

$$\overline{E} = \frac{1}{N}\sum_{i=0}^{N}\left|y_{\text{stylus}}(i) - y_{\text{laser}}(i)\right| \qquad (1)$$

An important problem with the roughness evaluation is a filtering of the surface profile.[19] Calculated roughness parameters significantly depend on the filtering method and filter cutoff frequency. Every filter distorts the real profile shape. In the experiment, high-frequency signals caused by electrical noise or wood anatomical micro-roughness were removed from the primary profile by a digital low-pass filter (cutoff 0.08 mm).

Results and discussion

Effect of sensor installation position

Figure 5 shows typical profiles obtained with the LDS positioned perpendicular and parallel to the scanned wood blocks with triangle shape type C. An important observation is that the shapes of both laser-scanned profiles differ significantly from the theoretical profile. Projection of the profile by a laser sensor situated perpendicularly proves to be much more comparable to the theoretical (and stylus-scanned) profile line. The determination coefficient (r^2) between the corresponding laser-scanned and theoretical

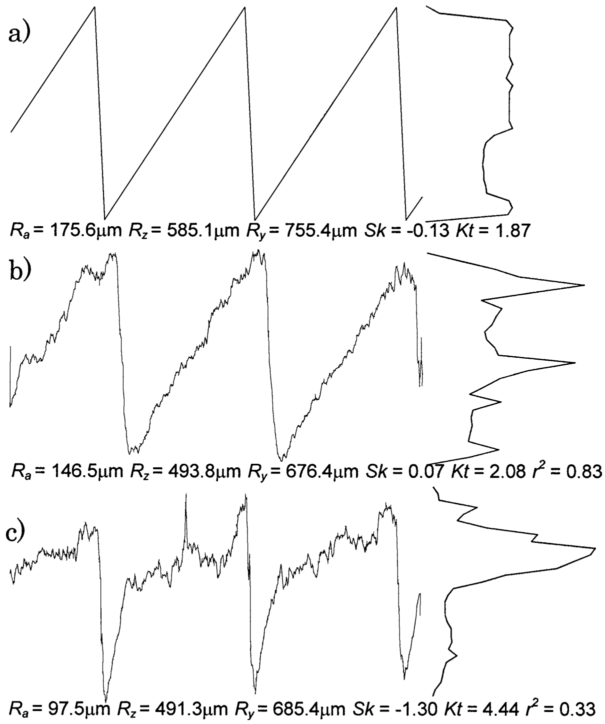

Fig. 5. Effect of the sensor installation position. **a** Theoretical profile. **b** Perpendicular position. **c** Parallel position. Wood species scanned was hornbeam

profiles in the case of a perpendicular LDS position was high ($r^2 = 0.83$), whereas in the parallel LDS position it was quite low ($r^2 = 0.33$). The R_z and R_y roughness parameters did not differ significantly for the two obtained profiles; however, R_a of the parallel measurement was about 50% lower than for the perpendicular LDS position. Examination of the profile height distribution (histogram) curve shows that the distribution of a perpendicularly scanned profile is platykurtic ($Kt < 3$) and not significantly skewed ($Sk \approx 0$). However, the distribution of a parallel scanned profile is leptokurtic ($Kt > 3$) and markedly negatively skewed ($Sk < 0$). It is evident from the above observations that the profiles scanned by the laser sensor installed parallel to the movement direction deviate from the real profile shape.

The parallel sensor's installation position is not favorable because of diverse scattering conditions while scanning different parts of the triangle profiles. It can be seen from Fig. 5c that representation of the shallow-sloped part of the profile is unacceptable, even though the steep part was scanned properly. In the first case, a large amount of light energy was reflected out of the detector, thereby following the regular reflection physical law. All fluctuations affected by shadowing, surface color changes, vertical oscillations and variations of workpiece conditions are amplified, when the light triangle's plane is parallel to the movement direction. Therefore, in the next investigations only the perpendicular installation position of the LDS is examined.

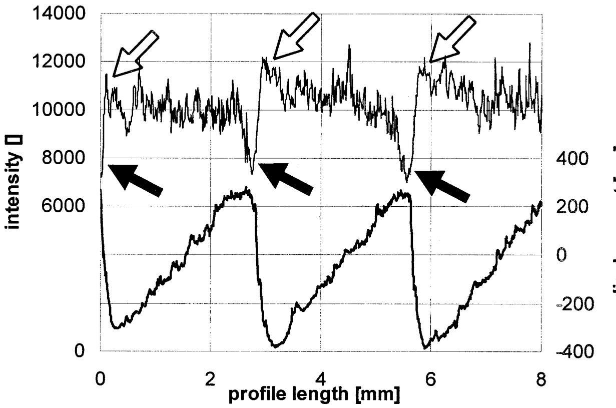

Fig. 6. Surface profile (*thick line*) and intensity of light reflected from the scanned surface (*thin line*) for scan triangle profile C ($\alpha = 15°$). *White arrows* indicate extra brightness of the laser light spontaneously reflected in the valley areas; *black arrows* indicate decreased light quantity in the profile peak areas. Conditions: hornbeam, laser sensor positioned perpendicularly

Intensity profile

A much smaller part of the laser light reflects into the detector direction from sloped surfaces than from flat surfaces, as shown in Fig. 6. When the angle between the laser beam direction and the surface plane was large, the intensity was high compared to the markedly sloped parts of the profile, where intensity was more than 30% lower.

On the other hand, light intensity increases when the profile's valleys are illuminated. When the light is shed on a valley, the beam is "trapped" inside, spontaneously scattering and illuminating the valley zone. In the experiment, that phenomenon was experienced as a "brightening" of the valleys when concave profiles were inspected. Another observation was that, in contrast to the previous observation, the intensity decreases dramatically at a peak. The reason is that the light focused on the profile tip reflects randomly, and consequently there is less light power acquired by the PSD. It should be noted that all profile peaks and valleys scanned by the LDS were somewhat rounded off.

These observations led to the conclusion that evaluation of the extreme parts of each profile results in measurement errors. The LDS has a tendency to "average" surface profile irregularities.

Effect of profile shape

Figure 7 shows three triangle profiles scanned by stylus and LDS. When a laser profile is compared with the stylus-scanned measurement, low-frequency waves are accurately reproduced, but high-frequency noise (oscillations around expected values) may be observed, especially in profile A. As mentioned above, laser-scanned profiles have rounded peaks and valleys. The roughness parameters R_a, R_z, and R_y calculated from laser-scanned profiles are smaller than the same parameters obtained by stylus for all profiles, although the Sk and Kt are similar.

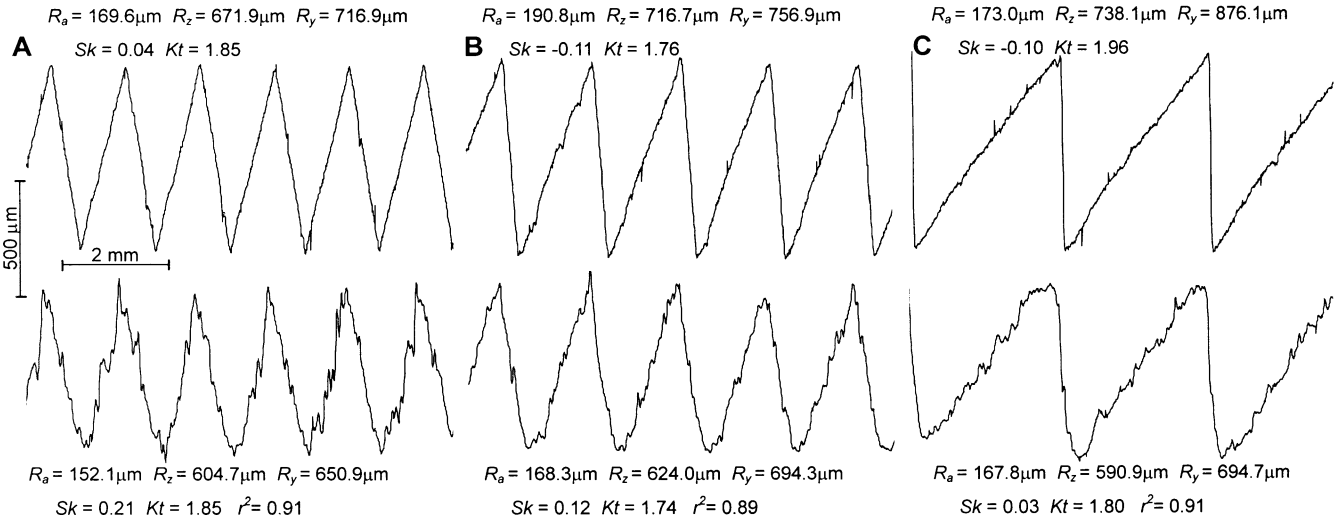

Fig. 7. Profiles **A**, **B**, and **C** scanned by stylus (*upper line*) and LDS (*lower line*). Conditions: hornbeam, laser sensor positioned perpendicularly

Effect of wood species

Figure 8 shows typical profiles obtained when LDS scanned various wooden blocks with triangle shape type A. As can be seen, all profiles were reproduced well. The shapes of the laser profiles were similar to the theoretical shape. However, it can be seen that some profiles differed slightly. The best imprinting of a profile is demonstrated by sakura (r^2 = 0.96), a medium-color, medium-density wood species. This observation is important because, as is explained in more detail later, LDS accuracy depends on wood color and wood density.

When wood density is low (meranti $\rho = 0.36\,\mathrm{g/cm^3}$) or high (keyaki $\rho = 0.76\,\mathrm{g/cm^3}$), the similarity to the theoretical profile decreases (Fig. 8). A similar phenomenon is observed when the color of the wood changes. The worst reproduced profile is an ebony profile ($\rho = 0.98\,\mathrm{g/cm^3}$), where the determination coefficient is the smallest among all wood species (r^2 = 0.56). Ebony's profile line oscillated around expected points (high-frequency noise). All roughness indicators calculated from the ebony profile are misrepresented, with the exception of R_a. Roughness parameters R_a, R_z, and R_y vary slightly in all other species, but Sk and Kt are similar to the expected values. R_z and R_y are lower because of the rounded profile peaks and valleys.

The above observations are summarized in Fig. 9. For the final analysis, an average error was chosen instead of the determination coefficient (r^2) because average error supplies a physical value that can be compared to the roughness descriptors. It may also be used to assess correction coefficients. Analyses of the determination coefficient r^2 provide results similar to those described below.

Accuracy (measured as an average error) changes with profile type, wood density, and wood color. The error is high when a steep profile (A) is scanned and low when a triangle profile becomes flat (C). A contour of the approximation function is more sphere-shaped in the case of profile A than the flat contour of profile C. Flat profiles are less sensitive to changes in the workpiece condition (density or

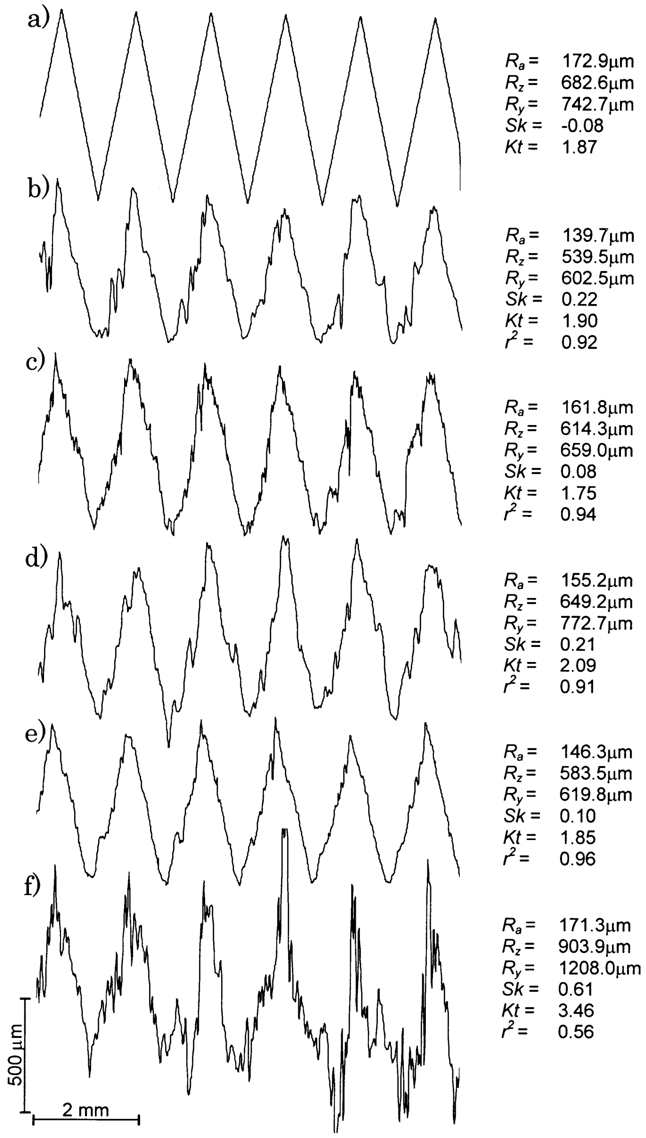

Fig. 8. Profile A for various woods scanned by LDS. **a** Theoretical profile. **b** Meranti. **c** Western hemlock. **d** Keyaki. **e** Sakura. **f** Ebony. Sensor positioned perpendicularly

color). The smallest error appeared when medium-density and medium-bright wood species are evaluated. The error increases when the workpiece becomes darker or brighter. Similar phenomena can be observed when wood density increases or decreases. That phenomenon can be considered the "special" behavior of the laser light on the porous wooden surface. The anatomical structure, anisotropy of wood properties, variation of wood colors, and other factors make an interaction between laser light and the wood surface complicated. In this research, only the effects of wood density and color were investigated.

It is well known that a dark surface absorbs light energy, and consequently only a small part of the light is reflected from the surface.[20] On the other hand, light emitted to a bright surface is reflected mostly by specular reflection. In addition, the laser spot increases its dimensions ("spills") on the light wood surface. A consequence is that only a small part of the laser light power emitted by the photodiode is reflected from a very dark or very bright surface into the detector. As a result, the signal-to-noise ratio increases and the LDS resolution decreases.

The effect of specific density may be described as follows. Laser light easily penetrates a low-density (highly porous) wooden surface. That makes volumetric scattering more significant, causing deformation of the laser spot. Moreover, the porosity of lightwood causes much more laser light dispersal and absorption than is seen with hardwood surfaces. However, when the laser light is focused on a high-density wood surface, the reflection changes from random scattering to a regular reflection. This is not an advantage because, for the triangulation method used in the sensor, a low amount of light energy reflects in the PSD direction from the surface. All of these phenomena impair the laser measurement.

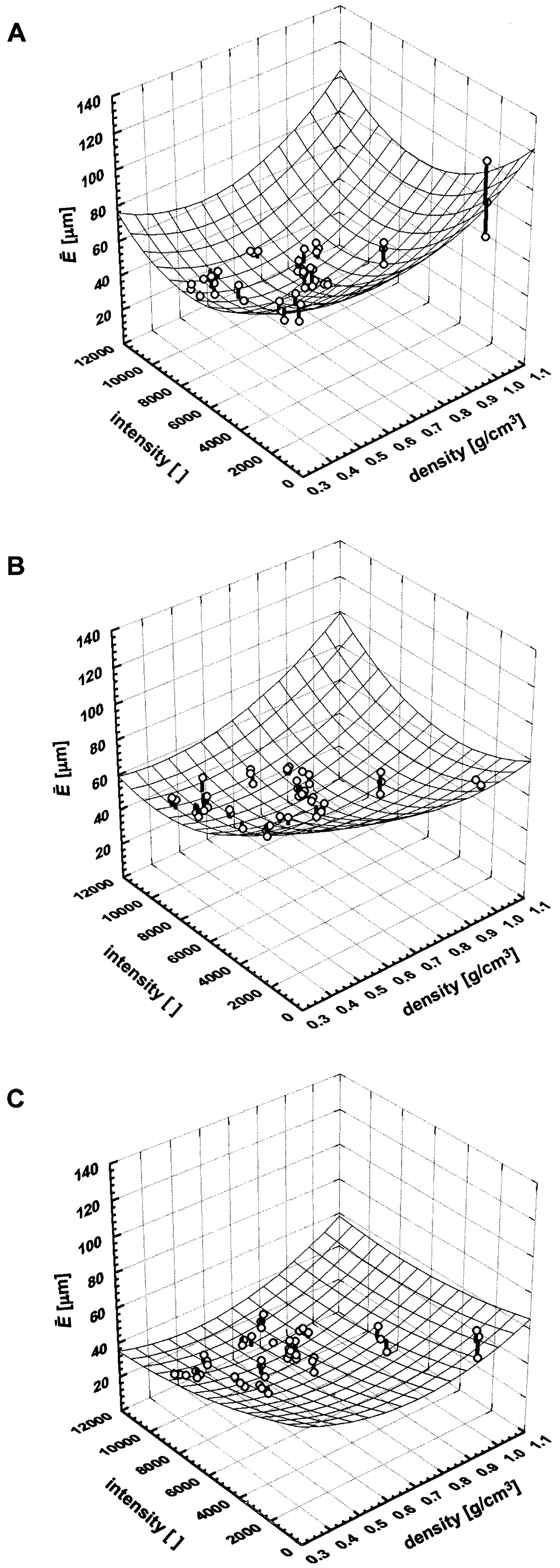

Fig. 9. Average error between stylus and laser profile points as a function of surface color and density of wood when triangle profiles **A**, **B**, and **C** were scanned. Laser positioned perpendicularly

Conclusions

Experimental results show that there is great potential for using LDS to evaluate wood surface smoothness, especially in on-line applications. Generally, all profiles were imitated properly, particularly when medium-darkness and medium-density wood profiles were scanned. Unfortunately, the investigated sensor has a number of limitations.

1. All laser-scanned lines tend to round off profile valleys and peaks.
2. Roughness parameters calculated from laser profiles differ slightly when different wood species were scanned. There is a need to evaluate some corrections of surface roughness descriptors calculated from laser-scanned profiles.
3. Laser displacement sensor accuracy decreases gradually when the specific density of the wood changes from medium to low or high.
4. Evaluation of very dark or very bright surface profiles is limited because of the LDS's tendency to generate high-frequency noise.

Experimental results demonstrate that profiles scanned by a laser sensor installed parallel to the movement direction deformed the real shape, indicated by a stylus profile. It is suggested that the LDS be installed perpendicular to the movement direction.

References

1. Shiraishi M (1986) Sensors and their applications in the manufacturing process. In: Japan–USA symposium on flexible automation, pp 827–830
2. Riegel A (1993) Quality measurement in surface technologies. In: International conference on woodworking technologies. Ligna, Hannover, pp 23:1–9
3. Lundberg IAS, Porankiewicz B (1995) Studies of non-contact methods for roughness measurements on wood surfaces. Holz Roh Werkstoff 53:309–314
4. Bonac T (1979) Wood roughness volume and depth estimated from pneumatic surface measurements. Wood Sci 11:227–232
5. Elmendorf A, Vaughan TW (1958) A survey of methods of measuring smoothness of wood. For Prod J 13:275–283
6. Nakamura G, Takachio H (1960) Reflection of light and roughness on sanded surface of wood. Mokuzai Gakkaishi 6:237–242
7. Lemaster RL (1997) The use of optical profilometers to monitor product quality in wood and wood-based products. In: Proceedings of the National Particleboard Association sanding and sawing seminar. Forest Product Society, Charlotte, NC, pp 33–42
8. Faust TD (1987) Real time measurement of veneer surface roughness by image analysis. Forest Prod J 37(6):34–40
9. Hagman O (1997) Multivariate prediction of wood surface features using an imaging spectrograph. Holz Roh Werkstoff 55:377–382
10. Bennett JM (1976) Measurement of the RMS roughness, autocovariance function and other statistical properties of optical surfaces using a FECO scanning interferometer. Appl Optics 15:2705–2707
11. Spurgeon D, Slater RAC (1974) In-process indication of surface roughness using a fiber-optics transducer. In: Proceedings 15th international machine tool design and research conference, Birmingham, UK, pp 339–347
12. Sprague RA (1972) Surface roughness measurement using white light speckle. Appl Optics 11:2811–2816
13. Funck JW, Forrer JB, Butler DA, Brunner CC, Maristany AG (1992) Measuring surface roughness on wood: a comparison of laser scatter and stylus tracing approaches. SPIE 1821:173–184
14. Stumbo DA (1963) Surface texture measurement methods. For Prod J 13(7):299–304
15. Keyence catalog 1999–2000 (1999) Keyence Corporation, Osaka, Japan
16. Radhakrishnan V (1970) Effect of stylus radius on the roughness values measured with tracing stylus instruments. Wear 16:325–335
17. Whitehouse DJ (1974) Theoretical analysis of stylus integration. Ann CIRP 23:181–182
18. Nakamura G (1966) On deformation of surface roughness curves caused by finite radius of stylus tip and tilting of stylus holder arm. Bull Jpn Soc Precis Eng 1:240–248
19. Fujiwara Y, Fujii Y, Sawada Y, Okumura S (2001) Development of a parameter to reflect the roughness of a wood surface that corresponds to tactile roughness. Holz Roh Werkstoff 59:351–355
20. Lemaster RL, Dornfeld DA (1983) Measurement of surface quality of sawn and planed surface roughness of wood product. In: Proceedings of the 7th international wood machining seminar. University of California Forest Product Laboratory, Richmond, CA, pp 52–70