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ORIGINAL

Method for evaluating the influence of wood machining conditions on the objective characterization and subjective perception of a finished surface

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Abstract A method for evaluating the influence of the operating parameters of wood machining (planing, sanding) on the quality of a finished surface was established. The influence of each of the operations involved was studied using different strategies. For the planing operation, three levels were established (Level 1, 2 and 3) by determining different values for each of the major process parameters (tool rotation speed, feed speed, depth of cut). For both, surface preparation and polishing, two levels were established with a fixed setup. Finally, as finishing products, two different transparent coatings were selected (water-borne and solvent-borne). The quantitative evaluation of the state of the surface was assessed by means of an artificial vision system for the determination of the pseudo-roughness of wood surfaces. A filtering method based on fast Fourier transforms was applied and it was possible to derive three criteria for evaluating the resulting profile.

Introduction

The finishing, i.e., application of a decorative and protective coating on the surface of the material, is the last operation in the manufacture of an object. The quality of the finishing can be assessed by objective parameters of performance

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related to the ulterior use of the finished object. However, the appearance of the finishing and its perception by consumers is equally important. The quality of a finished surface does not result only from technical characteristics of the applied product, but also from the application conditions. Preliminary operations like machining and surface preparation have a great influence too. The analysis of surface quality is also crucial for the successful control of quality in the wood manufacturing industries.

Wood machining

Wood is a complex heterogeneous polymer composed of cellulose, hemicelluloses and lignin, and its surface is influenced by several intrinsic factors of the material, namely the morphology of polymers, specific gravity, texture, roughness, extractives, moisture content and also by processing conditions (Côté 1983). The surface roughness of wood depends on both wood cellular structures and processing, and this characteristic has an important effect on the selection, application and service life of finishes (Williams et al. 1996).

The preparation of surfaces to receive finishing products includes operations like planing and sanding. Actually, a defective preparation often causes finishing defects, expressed as irregularities and inevitable deficiencies of the protective film built up by the finishing products, though it can happen that even the results of the application of excellent quality finishing products may have failures if the substrate surfaces are not in good condition. So, it seems that the state of the wood surface after machining (planing, sanding) affects the ability to receive a finishing product, either due to material intrinsic properties, or due to the surface roughness.

The great number of parameters of these operations and their interdependency make the study of the influence of wood machining on the state of wood surface very complex. Several studies were performed in order to provide information on the relationships between the key input variables of these operations and the surface of wood assessed by objective parameters like wood roughness.

Aguilera and Martin (2001) considered that the most important input parameters in the planing process were wood species, grain orientation, cutting depth, feed rate and cutting speed, and in the sanding process wood species, interface pressure, type of abrasive mineral, sanding orientation, feed rate and grit size (Carrano et al. 2004). However, studies relating wood machining to the quality of finishing are scarce (Fujiwara et al. 2004). On the other hand, only a few studies have considered the subjective characterization of the wood surface, such as it is assessed by the final consumers (Fujiwara et al. 2005). A first exploratory work made at ENSTIB demonstrated that parameters such as sanding grit size, depth of cut and feed rate of the machining operation, as well as the film thickness of coating products have a considerable influence on the quality of finishing, assessed by objective parameters and also subjective parameters (panel of observers; Moitie 1998).

Objective surface characterization

Wood surface can be characterized by using objective parameters such as roughness before and after finishing, brightness and colour of the finished surfaces, and wettability before and after finishing.

The evaluation of surface roughness of wood is a difficult task, because the roughness of wood is dependent on both cellular structure and processing. So, a suitable method should be used to assess the vision and tactile perception of a surface as it is taken by an observer. Several techniques used for other materials have been applied to wood, such as instruments that operate by contact (stylus, pneumatic, acoustic emission) or non-contact (optical; Lemaster 1995). The most common method uses a stylus instrument that mechanically measures the profile of the surface along a line in a selected small area of the surface. Several parameters are commonly determined from the resulting profile for roughness evaluation, but their signification is not fully understood in the case of wood (Krisch and Csiha 1999). Thus, a set of parameters that enable to distinguish particular types of roughness resulting from wood processing has yet to be established (Lemaster and Taylor 1999; Hendarto et al. 2006; Usta et al. 2007). A unique parameter will never be able to describe the quality of wood surface (Triboulot et al. 1991).

Another limitation in the determination of wood surface roughness is that neither specific instrumentation nor universal parameters have been developed so far (Krisch and Csiha 1999; Sandak and Tanaka 2003; Fujiwara et al. 2004). For instance, the filters described in the standards ISO 11562 (1996) and ISO 13565-1 (1996) have limitations when applied to wood surfaces (Gurau et al. 2005), due to distortions in the profile caused by wood anatomy (deep valleys), even though several authors proposed other filtering methods (Gurau et al. 2006) not yet included in the standards.

In order to assess the quality of wood surface, an adequate methodology capable of simulating the visual and/or tactile perception of aspect as “it is felt by an observer” has to be developed. At ENSTIB, two new methods were developed (Gross et al. 1996). One consisted of the characterization of the surfaces by friction analysis (TOPOSURF@) and the other one of an artificial vision system (TOPOVISE@), both object of patents. Compared to the mechanical measurement (stylus), analysis of the image is quick, cheap and inherently two-dimensional. Another work that uses an artificial vision system was presented by Kumar et al. (2005), but the method is very dependent on the natural characteristics of the surface, and in particular its chromatic variations. This work aims to improve the vision system developed at ENSTIB by finding a set of parameters/properties that could characterize the quality of the final aspect of a finished coated surface.

In addition, this study intends to determine the best machining operating conditions and application conditions for a good surface quality as felt by final users, on an industrial site and using common processing conditions. The assessment of the perception of surface state and subjective quality of the finishing will also be managed by means of a panel of observers.

Materials and methods

Sample preparation

The different parameters involved in surface preparation and finishing were grouped. In each group, several values and levels were selected (Table 1), taking into account the most commonly used values in the Portuguese furniture industry and the recommendations of the varnish manufacturers.

Flat-sawn boards of pine (density 510 kg/m^3, moisture content 9%) and beech (density 690 kg/m^3, moisture content 9%) of about 22 mm nominal thickness, previously kiln-dried, pre-cut and planed to a fixed dimension ($2.00 \times 0.10 \times 0.02$ m^3) were used. Then, the surface of the work pieces was prepared according to the protocol (Table 2), and 108 (18 for physical tests and 3×30 for processing) test pieces (0.20×0.10 m^2) of variable thickness were obtained from the initial 18 boards. Due to the inherent variability of wood, boards issued from the same log were used.

In order to permit online manipulation and to measure several operating conditions, the fourth element of a six-face moulder (upper face planner) was instrumented with: a high performance vector AC drive (to manipulate the cutting speed); a non-contact tachometer developed by the authors (to monitor the effective cutting speed); a voltage transducer and current sensors (to measure the power consumption).

Table 1 Factors and levels (species, pine P, beech B)

Levels/codes	Factors							
	Rotation speed, n (rpm)	Feed speed, f (m/min)	Depth of cut h (mm)	Grit size	Feed speed, f (m/min)	Thickness removed, h (mm)	Passages	Varnish layers
Machining								
L1	6000	6.5	1					
L2	5040	11	1					
L3	4080	18	1					
Sanding								
S0				–	–	–	–	
S1				(80,120)	10	0.5	1	
Polishing								
P0				–				
P1				400				
Finishing								
VC (solvent-borne)								1 + 1
VA (water-borne)								1 + 1

Table 2 Taguchi table

No.	Factors					Codes
1	P	L1	S0	P0	VC	− − − − +
2	B	L1	S1	P1	VA	+ − + + −
3	P	L1	S1	P1	VA	− − + + −
4	B	L1	S0	P0	VC	+ − − − +
5	P	L1	S1	P0	VA	− − + − −
6	B	L1	S0	P1	VC	+ − − + +
7	P	L2	S0	P1	VC	–0 − + +
8	B	L2	S1	P0	VA	+0 + − −
9	P	L2	S0	P1	VA	–0 + − +
10	B	L2	S1	P0	VC	+0 + − +
11	P	L2	S1	P0	VC	–0 + − +
12	B	L2	S0	P1	VA	+0 − + −
13	P	L3	S1	P1	VC	− + + + +
14	B	L3	S0	P0	VA	+ + − − −
15	P	L3	S0	P0	VA	− + − − −
16	B	L3	S1	P1	VC	+ + + + +
17	P	L3	S0	P0	VA	− + − − −
18	B	L3	S1	P1	VC	+ + + + +

For acquisition and control of signals, an application in LabView was developed.

The tool has two steel blades of 4 mm in thickness and a rake angle γ of 30° and is directly driven by an electric motor (nominal power 5.5 CV).

The sanding operation was carried out with an industrial sander "Boere", with control of the vertical position, the stress in the belts and the feed rate; the first roll was equipped with a belt (P80 grit sandpaper) and the second one with a P120 grit one.

Two varnishes, water-borne (acrylic resin; density = 1.03 ± 0.02 g/ml and Stormer application viscosity = 80–90 s, at 25°C; average film thickness = 25 μm and specific consumption = 13 m^2/l) and solvent-borne (nitrocellulose resins; density = 0.95 ± 0.02 g/ml and Ford cup number 4 application viscosity = 25–30 s, at 25°C; average film thickness = 25 μm and specific consumption = 10 m^2/l) were used. The product application was carried out directly on the prepared surface using an air-less gun following the manufacturer recommendations (spreading rates and drying conditions, etc.). The polishing of the varnish (prior to application of a second layer) was performed with a portable sander equipped with P400 grit sandpaper.

Objective surface characterization

For the characterization of wood surface, a new method based on the application of artificial vision methodologies was used, enabling the measurement of the apparent roughness of the wood surface. This method consists of illuminating the surface with a laser beam and recording the image (Fig. 1). This image has bright zones corresponding to peaks and dark zones corresponding to valleys. The apparatus is composed of a CCD BW video camera (model Sony XC-ST30), a video zoom lens (VZM300), an index-guide diode micro laser (VLM 10° line) and a single channel monochrome image acquisition board (NI1407). The equipment is connected to a PC computer running image acquisition and processing software IMAQ vision for Labview. The numerical treatment was performed with an application developed in Matlab.

From the images, the real roughness profile cannot be extracted but a "pseudo-roughness" profile can be established, to which a filtering method based on fast Fourier transforms (FFT) was applied. After a preliminary study, three criteria for evaluating the surface quality were chosen: a waviness criterion (K_{ond}) to assess the planed surface quality, a roughness criterion (K_{rug}) to assess the sanded surface quality and a subjective criterion (K_{sub}) to assess the finished surface quality. The waviness criterion was calculated from the value of the higher peak in the FFT power spectrum (Fig. 2) and the roughness criterion was obtained by numerical integration of the same curve. The subjective criterion was calculated by the ratio between the integral of the FFT power spectrum for wavelength inferior to the waviness minimal period (around 1 mm) and K_{rug}. These criteria were chosen because the method applied to extract the pseudo-roughness profile does not enable to calculate the standard roughness parameters as defined in EN ISO 4287 (1998) (Ra, Rz, etc.). The peak intensity (grey levels) is heavily dependent on the experimental conditions, though a frequency-domain analysis has to be performed.

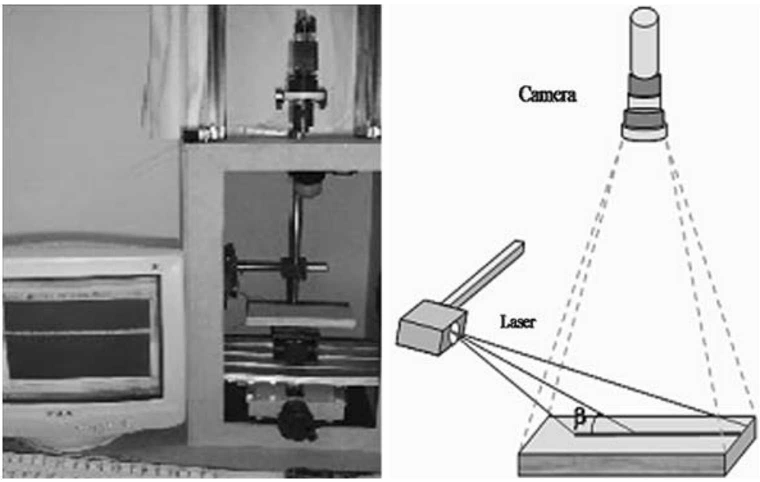

Fig. 1 Image and scheme of the laser vision system

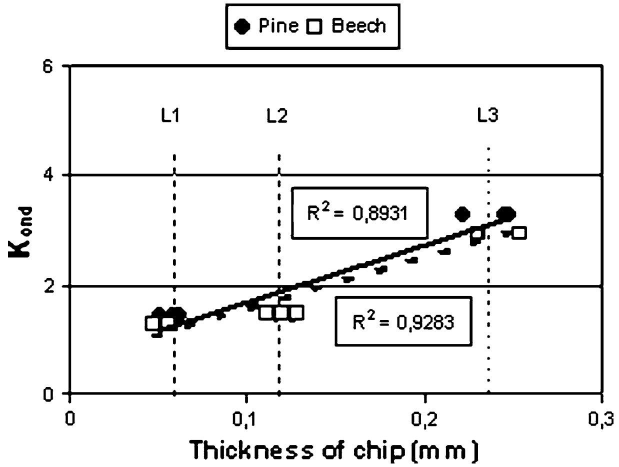

Fig. 2 Influence of machining level (chip thickness) on waviness criterion

Experimental protocol

Due to the great number of parameters to be studied, a statistical experimental design tool was used. Taguchi method was chosen and an L18 table was obtained (see Table 2).

In order to evaluate the significance level of the effects of the different factors, an analysis of variance (ANOVA) was performed.

Subjective surface characterization

The aim of the subjective analysis was to verify the existence of a correspondence between the objective characterization and the visual and tactile quality, and also whether there is a correlation between the criteria considered in the objective surface evaluation and the criteria considered in the subjective evaluation. To perform this study, enquiries to a sensory panel were carried out.

For the subjective analysis, the experimental protocol was established in accordance to ISO standards for sensory analysis, especially those that define the choice of the sensory panel members, the methodology, the preparation of the enquiry model, etc. [ISO 4121 (2003), ISO 5492 (1992), ISO 5495 (1983), ISO 6658 (1985) and ISO 11056 (1999)].

The surface characterization was performed with a sensory panel composed of six experts and six people with some experience in the field of wood (undergraduate students of wood engineering).

In this method, the sensory panel members evaluate the wood samples according to their own sensibility, and they assign these samples to a classification (Good–Bad), using both a simultaneously visual and tactile evaluation. All the panel members evaluated the same samples, a single sample for each of the 18 experiments.

A simple numerical treatment was applied to the results of the enquiries. To each classification, a numerical value was assigned: 1-Good; 2-Fair; 3-Bad. For each sample, the mean of the results of all enquiries was calculated. Three averages were considered: the mean of the results obtained by the experts, the mean of the results of the non-experts and a global mean.

Then the results of the subjective analysis were compared with the results of the objective analysis quantified by K_{sub}.

Results and discussion

The influence of the machining level (represented by chip thickness) in the criteria K_{rug} and K_{ond} are shown, respectively, in Fig. 2 and 3 for pine and beech. Its influence on the energy consumption per area is shown in Fig. 4. These plots display also the expected values of chip thickness for the three machining levels, as well as the tendency lines with the respective coefficient of determination. Figure 5 presents the waviness criterion (K_{ond}) as a function of the specific energy for the three machining levels studied.

In Fig. 2, we can see a strong influence of the machining level on the waviness criterion, which was expected due to the nature of this criterion. Furthermore, the relation between these two variables is not affected by the species factor. In the case of roughness (Fig. 3), an inverse behaviour is observed; thus, the roughness criterion is strongly dependent on the species, but is less affected by the machining level.

In Fig. 4, we can observe that the energy consumption increases from level 1 (L1) to level 2 (L2), but decreases from this one to level 3 (L3), which can certainly

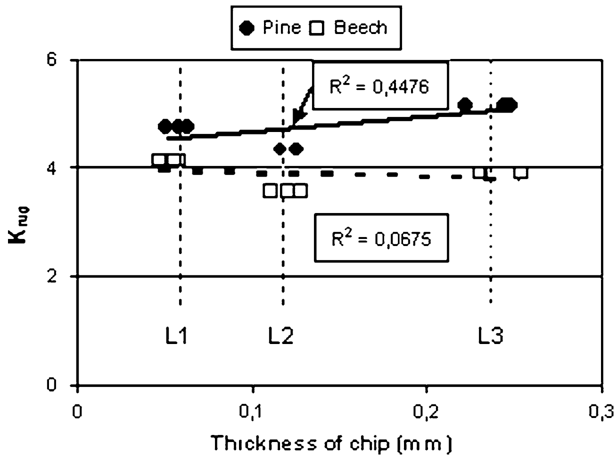

Fig. 3 Influence of machining level (chip thickness) on roughness criterion

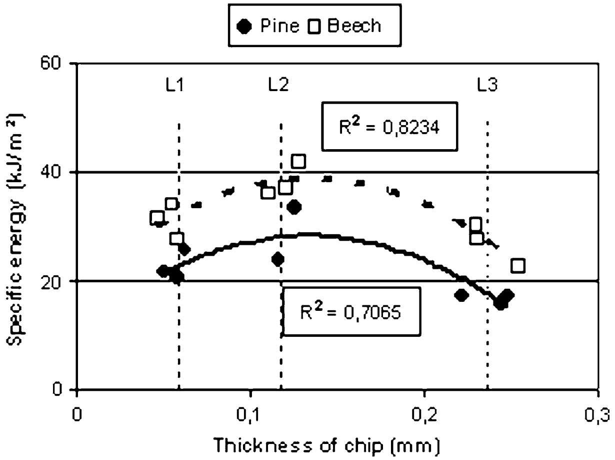

Fig. 4 Influence of machining level (chip thickness) on energy consumption per area

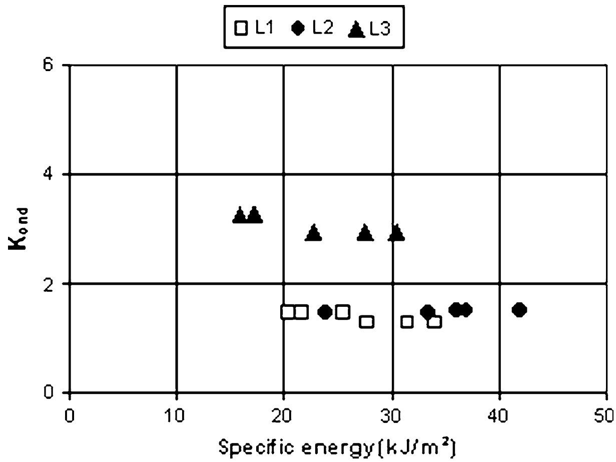

Fig. 5 Waviness criterion on function of energy consumption for the three machining levels

be related to the increase in the relative quantity of fibres pulled out from L2 to L3, resulting in a decrease in energy consumption. This conclusion is supported by Fig. 5, where an increase in energy consumption from L1 to L2 can be observed, which is not followed by a significant change in surface quality.

A strong dependency of the specific energy on the species factor is also observed. This can be attributed to differences in the anatomy and physico-mechanical properties of pine and beech.

Figure 6 compares the images, "pseudo-roughness" profiles and power spectra of FFT obtained with two machining levels of beech (tests 2 and 16 in Table 2). Globally, we observe an important quantity level of noise that cannot be filtered using this method, namely for higher frequencies (lower periods). The comparison of the two plots (different machining levels) indicates significant differences for higher periods, normally associated with waviness. These findings probably indicate that this method permits the estimation of the state of wood surface, because an average lower value of FFT power for machining level 1 (high rotation speed and low feed speed) was obtained, as expected.

Figure 7 presents the effects of the levels of the different factors in the criteria used for objective characterization of the surface (K_{ond}, K_{rug} and K_{sub}).

This analysis was carried out by calculation of mean and signal-to-noise ratio, being that the calculation of this last parameter was done taking into account *bigger is better*.

In Tables 3 and 4, the conclusions of this study (statistical significance level) are summarized. We can conclude that in order to obtain a little waved surface, the most important factor is the selection of the varnish (solvent-borne – VC). Nevertheless, the surface must be sanded and polished. Wood species and the level of machining are not significant. On the other hand, to obtain a slightly rough surface, the solvent-borne varnish used must be chosen. The others are not significant.

To obtain a good quality of the surface (as assessed by the final users), the solvent-borne varnish must be used and the surface must be polished. In this case, wood species as well as machining levels are not significant and sanding is of little significance. It is important to notice that this conclusion is similar for both mean and S/N ratio analyses.

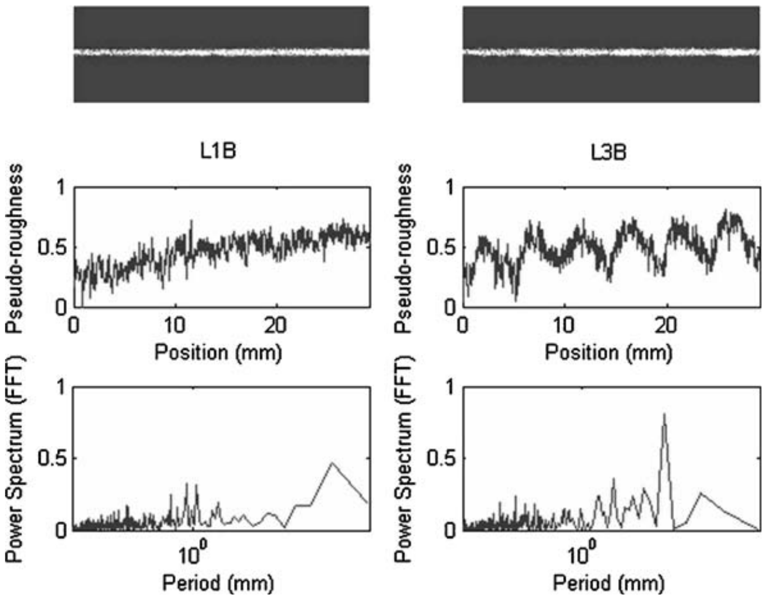

Fig. 6 Images of the surface, pseudo-roughness profiles and power spectra (FFT) of two beech samples, for the two machining levels L1 and L3

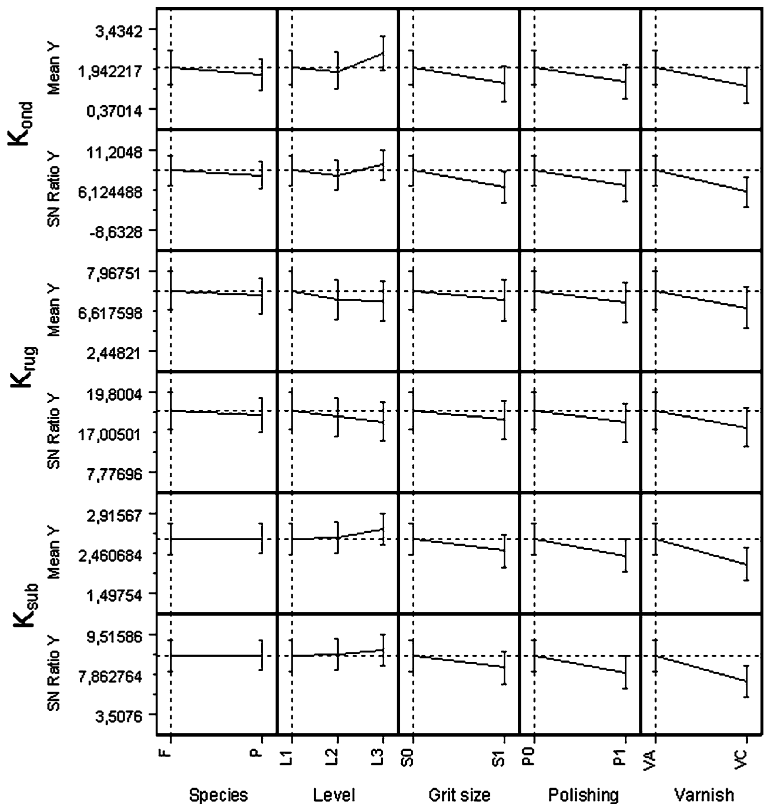

Fig. 7 Influence of the levels of the different factors on the criterion K_{ond}, K_{rug} and K_{sub} (mean/signal-to-noise ratio)

Subjective surface characterization

In Fig. 8, we present the means of the results of the vision–tactile analysis performed by the students and the experts on each sample. We can verify that these results are very similar both quantitatively and qualitatively.

Figure 9 shows the relation found between the objective criterion, K_{sub} and the global mean of the results of subjective analysis, and we can conclude that for both the species, there is a very good correlation between them. The subjective quality of the surface is then well described by the criterion K_{sub}.

Table 3 Statistical significance level of the effects of the different factors on the objective evaluation of surface quality mean (+5%, + + 1%, + + + 0.1%)

Mean	Species	Level	Grit size	Polishing	Varnish
K_{ond}	–	–	+	+	+ +
K_{rug}	–	–	–	–	+
K_{sub}	–	–	–	+ +	+ + +

Table 4 Statistical significance level of the effects of the different factors on the objective evaluation of surface quality- signal-to-noise ratio (+5%, + + 1%, + + + 0.1%)

S/N ratio	Species	Level	Grit size	Polishing	Varnish
K_{ond}	–	–	+ +	+ +	+ + +
K_{rug}	–	–	–	–	+
K_{sub}	–	–	–	+ +	+ + +

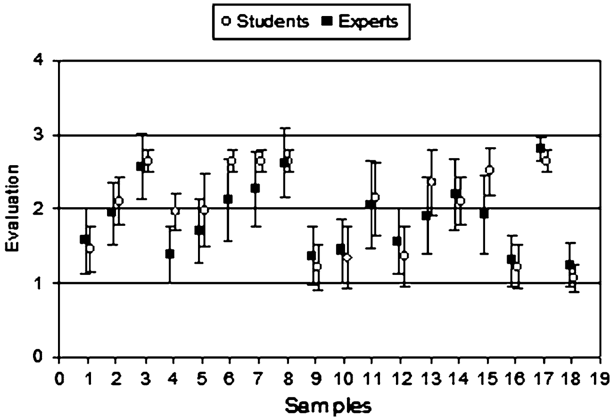

Fig. 8 Results of the vision–tactile analysis

Figure 10 shows values of the correlation coefficients between the criterion K_{sub} and the results of the assessment performed by each sensory panel member. It can be noticed that there is a good correlation for all members, except for the two represented with "x".

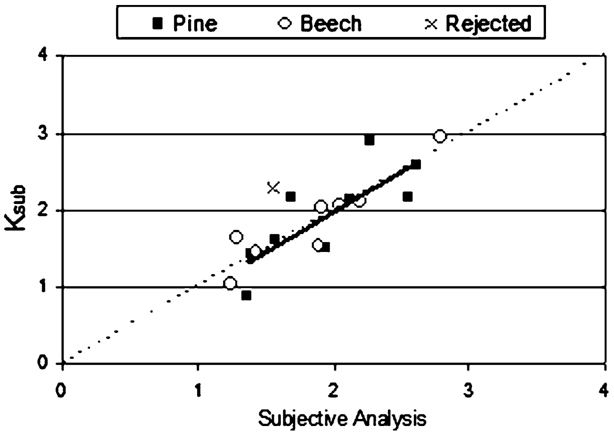

Fig. 9 Surface quality criterion (K_{sub}) versus human quality perception

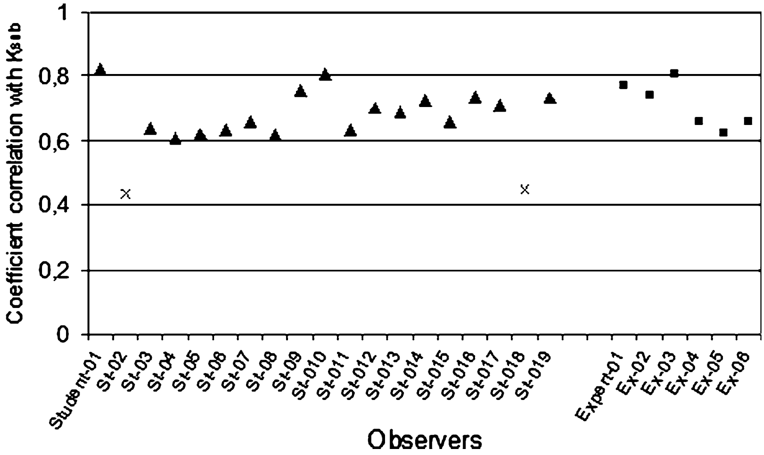

Fig. 10 Correlation coefficient between the objective criterion (K_{sub}) and the subjective evaluation for each sensory panel member

Conclusions

For a better understanding of the effects of the key operations of wood machining on the quality of a finished wood surface, obtained in industrial conditions (taking as reference the average values used in Portuguese furniture industry), some of the operations parameters were studied (two species, three machining levels, two sanding levels, two polishing levels and two varnish types).

The quantitative evaluation of the state of the surface was assessed by means of an artificial vision system for the determination of the pseudo-roughness of wood surfaces. A filtering method based on FFT was applied and it was possible to derive two criteria for evaluating the resulting profile: a waviness criterion (K_{ond}), a roughness criterion (K_{rug}) and a criterion close to the results of the subjective evaluation (K_{sub}).

Among the criteria that we have studied for the objective analysis, the waviness criterion (K_{ond}) and the roughness criterion (K_{rug}) show good correlations with the machining operations and the parameter K_{sub} with the subjective analysis.

Taking into account that we found an acceptable correlation between K_{sub} and the surface quality perceived by the final users, this criterion might eventually be used as a unique criterion for the evaluation of the whole process, at least for the conditions of the present work.

Considering the effects of the different factors, we observed that the most statistical significant factors are both the varnish type and the polishing schema. This observation does not indicate that the other parameters do not influence the surface quality, but that their influence is largely exceeded by varnish type and polishing schema.

Nevertheless, we can state that the best surface quality, as assessed by the final user, on both pine and beech is obtained by machining with level 1 conditions (feed speed = 6.5 m/min, rotation speed = 6,000 rpm, depth of cut = 1 mm) and the application of a solvent-borne varnish (two layers) using the finishing conditions indicated by the manufacturer (spreading rate, drying conditions, etc.) without the need of further operations (sanding, polishing). The application of a solvent-borne varnish always eliminates the need of a polishing operation. On the other hand, for the application of a water-borne varnish, there is always the need for polishing due to the fibres rising after the first layer application.

It is important to mention that the elimination of these operations (sanding and polishing) in the operative sequence usually performed in industry could bring, beyond the direct economical impact, a positive impact on both the working place environment and the eco-efficiency of the global process that could overcome the negative impact of using a solvent-borne varnish. This is a direct consequence of the decrease in energy and raw-materials (e.g. sandpaper) consumption and also a decrease in air-borne wastes (wood and sandpaper dust).

The results of this study, specifically the parameter K_{sub}, are a first step in the process optimization of the industrial operations involved, from planing to finishing, in the production of a wood product surface. Nevertheless, in a future work, we intend to explore the influence of different finishes on various wood species. Aspects regarding the finishing conditions, namely the type of finishing (open pores, close pores, semi-open pores), film thickness and number of layers (normally specified by the finishing products manufacturers) should be studied.

This is of major practical importance, mainly due to both the importance of these processes in furniture industry, and the fact that the choice of the proper type of product and operation parameters are often done empirically without any scientific or technological support.

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