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ASSESSMENT OF MACHINING PERFORMANCE FOR SOLID WOOD MOULDING. ADVANCES ON TRIALS RUNNING WITH SHARP CUTTING EDGE

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Abstract:

The final quality of solid wood moulding depends on several factors, being the raw material one of the most important, but the choice of cutting conditions are a key point when processing this type of material. One of the main problems is to achieve an adequate monitoring of the cutting conditions in order to detect and correct in-time operational problems or prevent the loss of productivity due to an over chute in quality at a level that is below the required standards.

The main objective of this research is to understand and limit the tool wear when appearance grade products are being produced, mainly to detect and prevent the loss of quality, but also the need to monitor the process considering different factors such as the cutting forces and the sound emitted during the process, then correlate them with surface roughness.

The main findings of this study allow to conclude that the relationship between cutting speed and feed rate reflects well the changes in cutting forces, surface roughness and sound pressure. When the chip thickness increases it correlates very well with increasing cutting forces, as well as surface roughness (good levels of coefficients of determination were observed for both response parameters), rougher surfaces produced with thicker chip (higher feed rate); but it is believed that in the present state of tool wear, the results of cutting forces have not a fully appropriate behaviour; further studies are needed on this variable at different levels of wear. Also, the change of rake angle is clearly reflected on the surface roughness and sound pressure. The RMS sound pressure provides adequate results when the signals were processed using a digital high-pass filter with a cut-off frequency of 1000 Hz.

Key words: *radiata pine; rake angle; sound pressure; surface roughness; wood machining; solid moulding.*

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INTRODUCTION

When processing kiln dried wood that is intended for added value products such as appearance grade, the surface quality resulting from the moulding process has critical importance. This process depends on several factors; the most important involve the chip-forming mechanism through machining kinematics where the sharpness, geometry and material of the cutting edge are basic parts of the resulting quality, and also the raw material in terms of moisture content and wood density. The resulting surface quality of wood-based machining products affects the quality of the adhesion between the surfaces or surface texture of the surface treatment.

Moreover, the evolution of tool wear when processing solid wood can be noted on various response parameters, becoming evident mainly with:

- Gradual increase of cutting forces and power,
- Progressive deterioration of the surface quality.

When determining cutting forces, the research should be aimed towards the chip formation process, the surface roughness and the tool life/wear of the cutting edge. The cutting edge recession has a gradual increase when both the time and the distance of the processed material increase. Additionally, the magnitude of the cutting edge recession and therefore the performance of the tool will be affected by the rake angle and the type of steel (cutting material). Moreover, operating conditions are related essentially to kinematic parameters of the cutting process, namely the relationship between cutting speed (Vc) and feed (Vf), cutting circle and depth and width of cut, all of which determines the chip thickness parameters and feed per knife or bite (fz), both related to cutting energy and surface quality.

A quality trait is the resulting surface roughness generated in the cutting process, where poor quality may be associated to a non adequate selection of cutting parameters, specifically the chip thickness, the cutting geometry and also the tool wear. According to Williams *et al*. (2000) the importance of the surface roughness on the surface coatings lies on the fact that it plays an important role in the performance and stability of the specific coating applied to the wood. Also, variations in surface roughness at different processing conditions have been reported by several authors: Davim *et al*. (2008, 2009), Hiziroglu and Kosonkorn (2006), Dippon *et al*. (2000), Aguilera *et al*. (2000), Lin *et al*. (2006), Akbulut and Ayrilmis (2006) and Engin *et al*. (2000), who reported surface quality problems that had been clearly linked to cutting conditions and raw material parameters. For example, Davim *et al*. (2009) evaluated the effect of cutting feed and speed on surface roughness, and concluded that the increase of spindle speed or the decrease of the feed rate provide smoother surfaces. Also, according to Aguilera *et al*. (2000), and Aguilera *et al*. (1999) the existing relation between the chip thickness and surface roughness is directly proportional, where a smooth surface is obtained with a small chip thickness, but with a decrease of tool life.

In order to monitor the cutting process one current applied method is, for instance, the power consumption (Murata *et al*. 1993). Iskra and Tanaka (2006) point out to that due to inert masses of the motor-spindle system the output signal is low-pass filter type, so the results are not accurate enough. Another method is the cutting forces measurement (Ko *et al*. 1999, Scholz and Hoffmann 1999), particularly useful to monitor the tool wear process. The method reported by Iskra and Tanaka (2006) requires the use of dynamometers, which are mounted between the spindle and the feed table, but have a negative influence on the dynamic stiffness of the tool-workpiece system. In this case, having the dynamometers and other contact sensors such as acoustic emission sensors is one main disadvantage. The fact that they need to be placed as close as possible to the cutting zone or in direct contact with the workpiece in the on-line manufacturing process, makes them not effective enough as an on line monitoring system. These acoustics signals are generated during the machining process, and can be captured directly from the wood vibrations using a piezoelectric transducer such as the acoustic emission sensors or dynamometers, or by means of a microphone-probe that captures the radiated sound. In this sense, Murase *et al*. (1993), Cyra and Tanaka (2000) and Murase and Harada (1995) made acoustics measurements in the wood cutting process searching for the effect of the cutting speed and the fibres angle on the chip formation process and the surface quality obtained.

Iskra and Tanaka (2005a) examined the possibility of using sound emissions (sound intensity and sound pressure) to monitor the cutting process of wood material, and concluded that there is a net relationship among the emitted sound and the cutting condition. They also established that sign filtering can be useful, the best correlation between roughness and sonorous intensity was obtained with sign filtering and using the centred third octave band in a 4kHz frequency. The same authors (Iskra and Tanaka 2005b) compared different analysis methods, for example the method of RMS average and the count rate, concluding that the most appropriate method was the RMS average which showed the highest correlation with the surface quality achieved.

Reiter and Keltie (1976) studied the effects of saw blade geometrics and kinematic parameters on idling circular saw noise. The authors found that variations in tool geometry produce effects in the radiated sound.

It is important to keep in mind the necessity of and accurate monitoring of the wood machining operations, since an efficient survey of the process allows to trigger an early alert for the operator to shut-off the machine before critical conditions are reached in terms of cutting speed or feed, making cutting forces and sound pressure interesting tools to correlate with surface roughness and then with tool wear. Consequently, the monitoring process is a very important element to consider in wood machining operations, because it seeks to improve performance by decreasing production times, always maintaining the quality standards.

The main objective of this research is to understand and limit the machining performance when appearance grade products are produced, assessing the relationship between the surface roughness, cutting forces and the sound pressure resulting from moulding operation on radiata pine solid wood.

MATERIALS AND METHODS

The trials were carried out using free of defects kiln dried radiata pine wood. Trapezoidal specimens of the following dimensions were used: 218mm length at the base (for the testing of cutting forces), 197mm top length, 39mm width, 40mm height (Fig. 1a). The cuts were performed on tangential growth rings of the specimens. Wood density and moisture content was measured in all samples prior to the tests. The operation was repeated with each sample after processing. In order to test the tool wear and sound pressure, samples had the same dimensions in cross section (39x39mm) but their length was 2.4 meters (Fig. 1b).

a. *b.*

Fig. 1

Wood specimens shape and dimensions. a - for cutting forces; b - for sound pressure and tool wear trials.

A Kistler measuring chain (Fig. 2) was used to measure the cutting forces: Kistler 9257B piezoelectric dynamometer, a charge amplifier Kistler 5070A1, data acquisition system Kistler 5697A1 and Dynoware 2825A software. 6 peak of cutting forces for each replicate were recorded.

A contact stylus Mitutoyo Sj-201 was used to measure surface roughness, characterised by a 5μm tip radius, a cut-off length of 2.5mm and five sampling lengths. The roughness parameter, “Rz” average height peak-valley (ISO 4287:1997) was considered to assess the surface characteristics of the samples. Surface roughness was measured following the cutting direction, performing 5 measurements for each repetition.

A single condenser microphone was used to measure the sound pressure signals. The microphone had a flat frequency response between 9Hz and 30kHz. The signals from the microphone were registered with a digital recorder (sampling rate 44.1kHz) and then transferred onto a computer for analysis. The RMS sound pressure (Pa^2) was calculated for each recorded sound signal.

The trials were conducted using three hydro-centred heads with variable cutting geometry, each one with 6 knives, freshly sharpened. The operating conditions are listed in Table 1.

a. *b.*

Fig. 2

Dynamometer chain measure. a – Dynamometer; b - charge amplifier and data acquisition system.

Table 1

Machining conditions

Variable		**Constant**	
Rake angle (°)	15, 20 & 25	Depth of cut (mm)	1
Cutting circle (mm)	192, 189 & 177	Width of cut (mm)	39
Cutting speed (m/s)	44, 50 & 56	Moisture content (%)	10.6
Feed (m/min)	4.1, 6.0, 7.6, 10.0, 12.0 & 14.0	Wood density (kg/m^3)	420
		Number of teeth	6
		Cutting material	HSS (6% W)

Rake angle (°)	**Cutting circle (mm)**	**Rotational speed N (1/min)**			**Cutting speed (m/s)**			**Delta knife projection (mm)**
15	192	4377	4974	5570	44	50	56	0.02
20	189	4446	5053	5659	44	50	56	0.01
25	177	4748	5395	6043	44	50	56	0.03

Note: HSS is High Speed Steel, W is tungsten

The cutting conditions were defined considering chip thickness "em" (mm) as a parameter that explains both the cutting forces and surface quality (Aguilera 2011, Aguilera & Méausoone 2012), it is directly related to the feed per knife (or bite) (fz) and the cutting height (ap) and inversely with the cutting diameter (D) as shown in the following expression [1]:

$$em = fz\sqrt{\frac{ap}{D}} \tag{1}$$

and fz (mm) relates to the feed speed as follows [2]:

$$fz = \frac{Vf}{N * Z} \tag{2}$$

Since the feed speed Vf is in m/min, the rotational speed of the spindle N in 1/min and Z the number of knives.

And finally the cutting speed Vc (m/s) [3]:

$$Vc = \pi * \mathbf{D} * \mathbf{N} \tag{3}$$

Before the final installation of the recording acoustic signals system, some preliminary measurements should be performed. It is important to review, and if necessary correct, details like microphone placement, calibration of signal recording, recording levels, etc. Furthermore, preliminary measurements allow to define the set of descriptors that characterise the signals for later analysis. Basically, there are established frequently used statistical descriptors such as RMS. The following value [4] returns for each recorded signal:

$$RMS = \sqrt{\frac{1}{N}\sum_{1}^{N}(x_i - \mu)^2} \tag{4}$$

$\mathbf{x_i}$: discrete values of the signal
µ: average values $\mathbf{x_i}$
N: number of samples

RESULTS AND DISCUSSION

Raw material

The results of radiata pine wood density indicate that normal values are found for this type of timber, with an average density of 417kg/m^3 and a relatively low standard deviation, with most samples being concentrated between 380 and 480kg/m^3. With regard to the moisture content, an average of 10.6% was determined, concentrated between 8.3% and 13%, with a low standard deviation, where only three values reach about 15%. Therefore, wood density and moisture content show a normal distribution (considering 270 samples).

Cutting forces and surface roughness

Fig. 3, 4 and 5, and Tables 2 and 3 show the results of cutting forces and surface roughness. It can be observed in Fig. 3 to 5 the trend of increased cutting forces when the chip thickness increases (mainly as a response to feed rate increase); however, because the chip thickness levels are very small there is not a clearly visible differentiation between the rake angles. Also, there is not a clear difference for cutting speed with slightly higher average values for the cutting speed of 56m/s, however, it is expected that with the extent of the tests at higher feed rates it may be possible to have a full vision of the cutting behaviour for this speed.

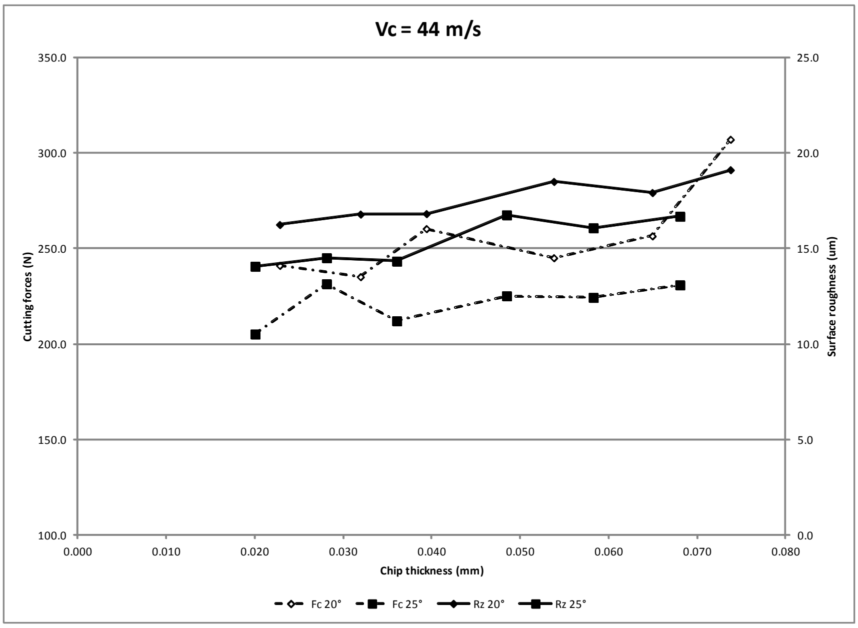

Fig. 3
Cutting forces Fc (N) – surface roughness Rz (µm) for 44 m/s of cutting speed according to chip thickness (mm) and rake angle.

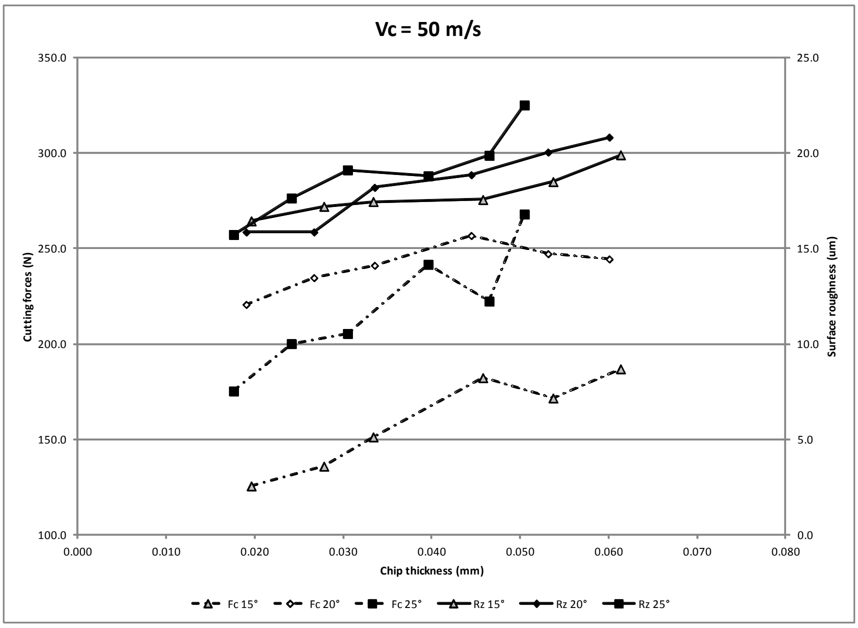

Fig. 4
Cutting forces Fc (N) – surface roughness Rz (µm) for 50 m/s of cutting speed according to chip thickness (mm) and rake angle.

In the particular case of Fig. 3, it is possible to observe an acceptable performance of cutting forces at 44m/s for a rake angle 20 and 25°, but with a low coefficient of determination. The results show an increase of cutting forces when lowering the cutting speed, while a low level of cutting force is obtained with the increase of the rake angle when comparing the overall mean values. A particular situation which require more research are the lower values of cutting forces found with 15° rake angle compared to the others.

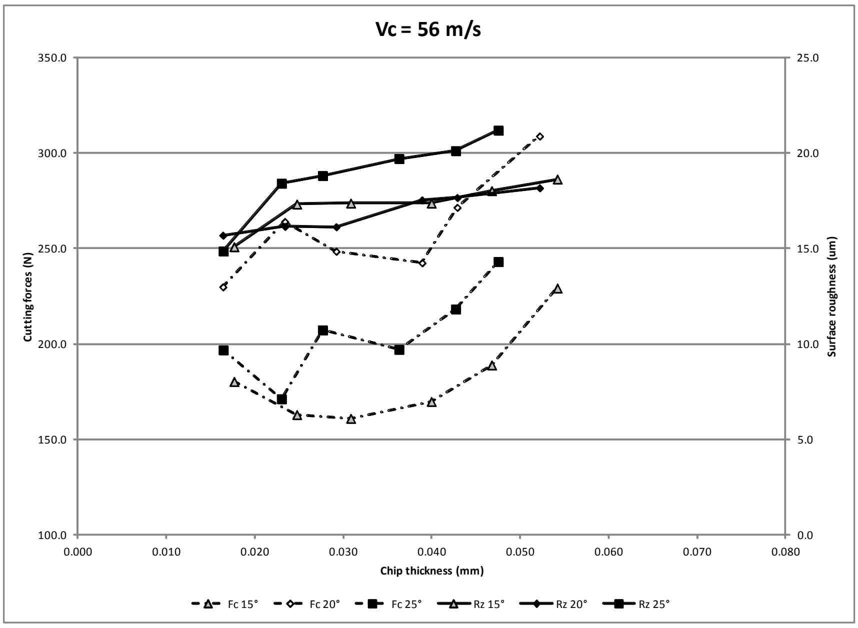

Fig. 5
Cutting forces Fc (N) – surface roughness Rz (µm) for 56 m/s of cutting speed according to chip thickness (mm) and rake angle.

Table 2 shows the equations of cutting forces as a function of chip thickness, and the coefficients of determination, in general with acceptable results at all cutting speed and rake angle but with low coefficients for 56m/s of cutting speed and 15° rake angle and 44m/s of cutting speed and 25° rake angle. The variations may be caused mainly by the effect of the heterogeneity of the wood samples (wood density). The moisture content (MC) and cutting depth effect is not significant because the variation of MC was low (4% difference), and cutting depth remained at 1.1mm.

Table 2
Cutting forces (Fc) and surface roughness (Rz) functions and determination coefficient (R2) to chip thickness (e) by cutting speed and rake angle

Cutting speed (m/s)	Rake angle (°)	Cutting forces	R^2 (Fc)	Surface roughness	R^2 (Rz)
44	15	Fc = 2417.8 e + 86.715	0.988		
50	15	Fc = 1492 e + 98.888	0.897	Rz = 70.177 e + 15.013	0.871
56	15	Fc = 1301.9 e + 135.57	**0.499**	Rz = 75.910 e + 14.586	0.762
44	20	Fc = 993.21 e + 210.09	0.567	Rz = 53.021 e + 15.031	0.871
50	20	Fc = 583.33 e + 217.78	0.567	Rz = 128.0 e + 13.216	0.948
56	20	Fc = 1646.7 e + 205.15	0.615	Rz = 75.055 e + 14.349	0.948
44	25	Fc = 350.26 e + 206.41	**0.367**	Rz = 59.954 e + 12.813	0.793
50	25	Fc = 2312.8 e + 138.35	0.829	Rz = 161.54 e + 13.321	0.846
56	25	Fc = 1563.5 e + 155.2	0.604	Rz = 167.2 e + 13.451	0.838

Regarding the surface roughness, Fig. 3 to 5 show a similar behaviour between the cutting forces and the surface roughness, with both response parameters registering ascending values when increasing chip thickness, i.e. higher cutting forces and increased chip thickness result in a rougher surface; a similar behaviour is also observed at different rake angles and cutting speed. Still, the expected result was to find a smoother surface with a smaller chip thickness, with an increase of cutting speed and rake angle. However, at this stage of the research the findings are not so clear because the cutting edge is at a running level (less than 100 meters of cutting distance), but the coefficients of determination (Table 2) for the surface roughness are very good at all cutting conditions levels, where the chip thickness may explain satisfactorily the surface roughness.

Sound pressure

The emitted sound under different operating conditions was registered as a first review of the intensity of the generated signals. Besides the analysis of the signal in the time domain, it is important to consider the spectral characteristics of the emitted signals. Indeed, it is in the frequency spectrum where the periodic behaviour of the machining process involved is clearly expressed, through the appearance of pure tones components and corresponding harmonics. The frequency of these components depends on the spindle rotation speed and the number of knives. The corresponding amplitude should be influenced by factors such as the situation with or without charge, the state of the knives, the type of wood etc. Fig. 6 illustrates a detail of the two spectra where it can be clearly appreciated the difference between a loaded and an unloaded situation.

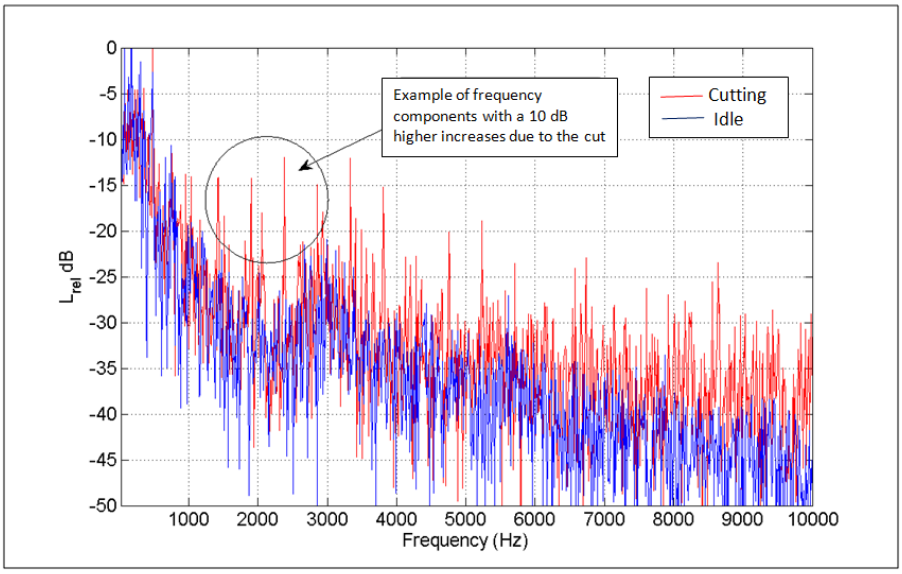

Fig. 6
Comparison of spectra, relative to the maximum load level Lrel.

Table 3 provides the results for the correlation coefficient R^2 obtained for different machining conditions.

Table 3
Results for the correlation coefficient R2 obtained for different machining conditions, considering as variables the feed speed and the RMS descriptor with and without processing the signals using digital filtering (high-pass)

Rake angle (°)	Cutting speed (m/s)	R^2 RMS
15	44	1.00
15	50	0.92
15	56	0.98
20	44	0.96
20	50	0.94
20	56	0.91
25	44	0.96
25	50	0.97
25	56	0.92

In general, the best performing descriptor is the RMS which is directly related to the energy content of the signal. While signal analysis for predictive maintenance applications often use different descriptors (Crest Factor, skewness, kurtosis), in this case study the RMS sheds interesting correlation values. Although the fundamental components of the signals are located in the low frequency range, the comparing case with and without load (Fig. 6) shows that the signal due to cut is clearly distinguishable from the emission unloaded (idle) only from a frequency of 1000Hz. The findings confirm the influence of the sound emitted by the machine (idle), which can produce low frequency variations that are not necessarily related to the feed speed or cutting. This confirms the need to modify the frequency response and consider only signal components in the frequency range where the noise emission with and without load are clearly differentiated. Consequently,

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the signals were processed using a digital high-pass filter with a cut-off frequency of 1000Hz. A Butterworth digital filter was used at the processing.

The results confirm the convenience of filtering the signals and focus the analysis on the higher harmonics from the 1000Hz. Fig. 7 to 9 show as examples the results of sound pressure (RMS) for constant cutting speed and different rake angle.

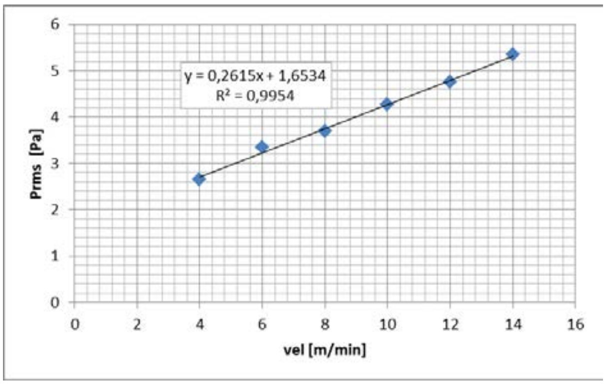

Fig. 7
Results for sound emission (RMS pressure) depending on the feed speed. Condition: rake angle 15 °, cutting speed 44 m/s (rotation 4377 rpm).

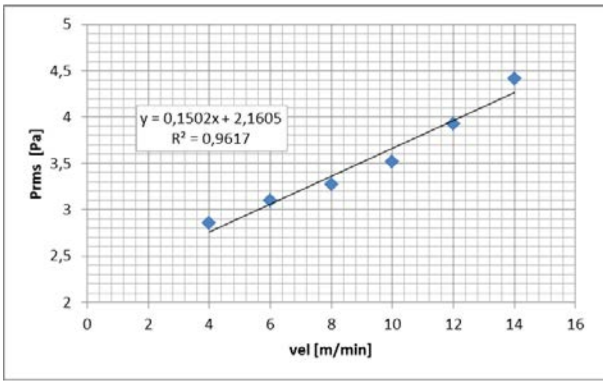

Fig. 8
Results for sound emission (RMS pressure) depending on the feed speed. Condition: rake angle 20 °, cutting speed 44 m/s (rotation 4446 rpm).

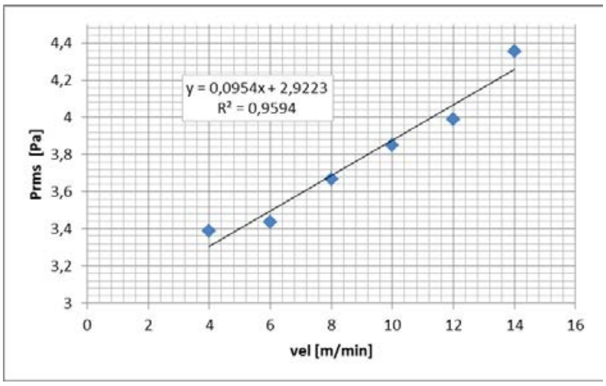

Fig. 9
Results for sound emission (RMS pressure) depending on the feed speed. Condition: rake angle 25 °, cutting speed 44 m/s (rotation 4748 rpm).

In general, as shown Fig. 7 to 9, there is a rise of the sound pressure with the increase of feed speed, while the increase of the rake angle causes a decrease in sound pressure. These results are satisfactory and comparable when the cutting speed is increased. Further analysis is needed to compare sound pressure with cutting forces and surface roughness.

CONCLUSIONS

At this research phase, interesting results were achieved on the processing of radiata pine solid wood for appearance grade products (decorative mouldings). As a first stage, we worked with high speed steel (HSS) freshly sharpened, i.e. at running stage. We analysed the change of machining conditions in terms of cutting speed and feed rate, and the cutting geometry mainly the rake angle, studying the cutting forces, surface roughness and sound pressure. Under these conditions, we can conclude the following:

- The relationship cutting speed and feed rate expressed as chip thickness reflects well the changes in cutting forces, surface roughness and sound pressure.
- Increased chip thickness correlates very well with increasing cutting forces, with good levels of coefficient of determination.
- Increased chip thickness correlates very well with the deterioration of the surface, rougher surfaces produced with thicker chip (higher feed rate) observed good levels of coefficients of determination.
- The change in the rake angle is clearly reflected in the surface roughness and the sound pressure.
- It is believed that in the current state of tool wear the results of cutting forces have not fully appropriate behaviour, this variable will continue to be studied at different levels of wear.
- The RMS sound pressure provides adequate results when the signals are being processed using a digital high-pass filter with a cut-off frequency of 1000Hz. A Butterworth digital filter was used during the processing.

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