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SOUND PRESSURE AS A TOOL IN THE ASSESSMENT OF THE SURFACE ROUGHNESS ON MEDIUM DENSITY FIBREBOARD RIP SAWING PROCESS

***Alfredo Aguilera*[1] *, Jose Luis Barros*[2]**

ABSTRACT

This research takes the option of using sound pressure signals to monitor the resulting surface roughness from rip sawing process of medium density fibreboards samples. Different cutting conditions were evaluated, namely cutting speed and feed, giving as a variable the mean chip thickness, being also assessed the effect of the climb cutting and conventional cutting mode. The main results lead to conclude that the sound pressure was closely related to the variation of the mean chip thickness giving adequate levels of correlation with the surface roughness. A positive, linear relationship was observed between feed rate and surface roughness, as well as for sound pressure. The best surface quality was achieved when climb cutting mode was applied. Then, the measurement of sound pressure results is a useful method to monitor MDF cut process, being possible to predict the surface roughness, as well as the effect of the change of cutting conditions.
Keywords: Sound pressure, circular saw, MDF, surface roughness.

RESUMEN

Esta investigación considera la opción de usar las señales de presión de sonido para monitorear la rugosidad superficial resultante del proceso de corte longitudinal con sierra circular de paneles de densidad media. Se evaluaron diferentes condiciones de corte, en particular la velocidad de corte y de avance, entregándose como variable el espesor medio de viruta, también se estudió el efecto del modo de corte convencional o concordante. Los principales resultados indican que la presión de sonido se correlacionó muy bien tanto con la variación del espesor medio de viruta como con la rugosidad superficial. Una relación lineal positiva se observó tanto entre la tasa de alimentación y la rugosidad, como también con la presión de sonido. La mejor calidad de superficie se obtuvo con el modo de corte en concordancia. Los resultados de la medición de presión de sonido son un método útil para controlar el proceso de corte de MDF, siendo posible predecir la rugosidad superficial y el efecto del cambio de las condiciones del proceso.
Palabras clave: Presión de sonido, sierra circular, MDF, rugosidad superficial.

INTRODUCTION

Medium density fibreboard (MDF) panels are a raw material widely used in decorative mouldings and furniture applications, being the apparent resultant quality of this panel on their surfaces or edges influenced by the appearance of its machined surface, surfaces that will receive surface coatings. One of the main cutting processes in this type of material is the rip sawing, employed to calibrate and generate intermediate or final dimensions or even surface finishes, although sometimes generating problem of bad quality when any surface irregularities are exposed due in part to inadequate cuttings conditions or because a deficient monitoring process. Consequently, the monitoring process is a very important element to consider in wood machining operations, mainly because it seeks to improve performance, always keeping the quality standards. A quality indicator of the cutting processes of boards are for example the straightness of the cut, burning surfaces, chipped edges and the roughness generated at a determined machining operation; a rougher surface may be associated to a poor selection of cutting

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conditions, i.e. the mean chip thickness, the cutting geometry and tool wear (Kivimaa 1950). The surface coatings are closely linked with the surface roughness by the fact that the roughness plays an important role in the performance and stability of the specific coating applied to the wood. Difference in surface roughness at changed cutting conditions for MDF have been reported by Kilic *et al*. (2006), Davim *et al*. (2009), Davim *et al*. (2008), 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), where surface quality problems are related to the change of cutting conditions and also with raw material characteristics. For example, in a study on MDF milling, Davim *et al*. (2009) evaluate the effect of cutting speed and feed rate on the surface roughness, concluding that the increase of spindle speed or the decrease of the feed rate, provide best results of quality. Also, studies carried out by Aguilera *et al*. (2000), Aguilera *et al*. (1999) indicate the existing relation between the chip thickness and surface roughness, being this directly proportional, where a smooth surface is obtained with a small chip thickness, although with a high energy expense; and with a decrease of tool life.

A method that allows the supervising and monitoring of the cutting process is for instance the power consumption (Murata *et al*. 1993); however, Iskra and Tanaka (2006) indicate that due to inert masses of the motor-spindle system, the output signal has a lowpass filter characteristic, with the results not being accurate enough. Other method is cutting forces measurement (Ko *et al*. 1999, Scholz and Hoffmann 1999), particularly useful to monitor the tool wear process. This method requires the use of dynamometers, which are mounted between the spindle and feed table, but have a negative influence on the dynamic stiffness of the tool-workpiece system (Iskra and Tanaka 2006). In this case, dynamometers and other contact sensors like acoustic emission sensors have 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, making them not effective enough for an on line control-monitoring system. These acoustics signals are generated during the machining process, which can be captured directly from the wood vibrations by means of a piezoelectric transducer (acoustic emission sensors or dynamometers) or by means of a microphone-probe that captures the radiated sound (vibratory signs). Murase *et al*. (1993), Cyra and Tanaka (2000) and Murase and Harada (1995) develop acoustics emission measurements in wood cutting searching the effect of the cutting speed and the fibres angle, the results indicate that the generated signals are very well correlated with both the cutting process characteristics (chip formation) and the surface quality obtained.

Sound signals measures have been employed in metal-cutting processes: Trabelsi and Kannatey-Asibu (1991) analyzed the pattern-recognition analysis of sound radiation, recording the sound-pressure signals radiated during cutting under fixed conditions using a sharp tool, a worn tool and a broken tool. Tekiner and Yesilyurt (2004) evaluate the best suitable cutting conditions and cutting parameters, concluding that the best cutting parameters could be determined depending on the sound.

Iskra and Tanaka (2005) examined the possibility of using sound emissions (sound intensity and sound pressure) to monitor the cutting process of wood material, concluding that there is a clear relation among the sound emitted and the cutting condition. Besides, they 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 4 kHz frequency. The same authors (Iskra and Tanaka 2005b) compared different sound emissions analysis methods, 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. Others studies conducted by Darmawan *et al*. (2000) on wood based materials, evaluated the cutting performance of some coated carbide tools, where the tool wear, normal cutting force and sound pressure level were measured to evaluate the cutting performance, reporting as main results that the normal force and sound pressure level increased when increasing tool wear. The relationship between cutting sound and tool wear in machine boring of wood and wood-based materials was studied by Banshoya *et al*. (1994), the authors concluded that measuring the sound pressure level was promising for the in-process detection of tool wear of machine boring bits.

In circular saws, Reiter and Keltie (1976) developed an experimental investigation of the effects of saw blade geometric and kinematic parameters on idling circular saw noise. The authors found that variations in blade geometry produce effects in the radiated sound. Goglia and Belio-Lucic (1999) studied for differently designed circular saw blades the noise level and noise frequency, where the sound pressure level was measured at different rotational frequencies. They found that the relation between sound pressure and peripheral velocity can be described by a linear equation with a high correlation coefficient.

The objective of this research is to assess the relationship between the surface roughness and the sound pressure resulting from the rip sawing operation on MDF material, evaluating the consequences of a change of the mean chip thickness and the cutting mode.

MATERIALS AND METHODS

A 15 mm thickness MDF light commercial-type was tested, having 600 kg/m^3 average specific gravity and 9.3% of moisture content. A total of 32 samples were extracted randomly from one board, having dimensions of 400 mm length and 120 mm width. The samples were machined in a single-spindle shaper machine, where both the cutting speed and feed were controlled. For the rip sawing process, a sharp tungsten carbide (HW) with alternate top bevel tooth design (ATB) circular saw was involved in the trials, as described in Table 1.

Table 1. Linear and geometrical parameters of circular saw

Linear Parameters		**Geometric Parameters**	
Number of teeth	34	Rake angle	20º
Tooth pitch	18.5 mm	Sharpness angle	50º
Tooth height	10.7 mm	Clearance angle	20º
Saw kerf	3.2 mm	Top clearance angle	14°
Saw thickness	2.2 mm	Side clearance angle	5°
Saw diameter	200 mm		

The studied variables were the chip thickness (determined according to Aguilera 2010) that depends of four levels of feed speed, the cutting mode: climb cutting and conventional cutting operation (defined by Aguilera 2010b), and the cutting speed of 44.5 and 62.8 m/s that match with 4250 and 6000 rpm of rotational speeds respectively. The factorial experimental design is presented in Table 2. Ten repetitions were carried out for every chip thickness, giving a total of 80 measures of surface roughness and sound pressure in each cutting mode.

Table 2. Experimental design for the circular saws and corresponding mean chip thickness

Cutting speed (m/s)	Feed speed (m/min)	Theoretical Mean chip thickness (mm)	Feed per tooth fz (mm)
44.5	4.2	0.014	0.029
44.5	8.4	0.028	0.058
44.5	10.8	0.036	0.075
44.5	21.5	0.072	0.149
62.8	4.2	0.010	0.021
62.8	8.4	0.020	0.041
62.8	10.8	0.026	0.053
62.8	21.5	0.051	0.105

Note: Override (f) 6 mm, cutting height 15.2 mm

The measurements of surface roughness were conducted with a “stylus” contact roughmeter, characterized by a 5 µm tip radius, a cut-off length of 2.5 mm and 5 sampling lengths. To assess the surface characteristics of the samples, the roughness parameter “*Rz*” average height peak-valley (ISO

4287 1997) was considered. After each cut the remaining specimen of 400 x 15 mm was evaluated by measuring its roughness in three points, the edge, the middle and the core of the panel, so the mean value of the roughness profile was used to determine its relationship with the sound pressure.

Sound pressure is the force of sound on a surface area perpendicular to the direction of the sound, where the sound is measured with microphones that respond proportionally to the sound pressure, being the power in a sound wave equal to the square of the pressure (Pa^2). Then, for the sound pressure measurement a matched pair of condenser microphones were employed, which had similar open-circuit sensitivity, frequency, and phase response characteristics. The microphones have a flat frequency response between 9 Hz and 30 kHz. The signals from the microphones were registered in a digital recorder (sampling rate 44.1 kHz) and then transferred to a computer for analysis. The RMS sound pressure was calculated for each recorded sound signal. One microphone was fixed at about 20 cm from the cutting zone, the other was opposite at 100 cm distance. The room area was free from surrounding noise.

RESULTS AND DISCUSSION

Variation of feed speed on surface roughness and sound pressure

Table 3 and 4 shows the results of surface roughness (mean/standard deviation) measured at the three layers of the panel profile, for conventional and climb cutting at each cutting speed and feed speed including the mean result of the entire profile.

Table 3. Surface roughness *Rz* (µm) by cutting mode and layer of the panel profile

Cutting speed (m/s)	Feed speed (m/min)	Surface roughness Rz (µm) Conventional cutting				Surface roughness Rz (µm) Climb cutting			
		Edge	Middle	Core	Profile Mean	Edge	Middle	Core	Profile Mean
44.5	4.2	60.50/13.11	98.78/13.98	109.52/16.33	89.60	61.16/4.93	71.21/4.20	72.60/6.31	68.33
44.5	8.4	65.57/11.12	104.91/17.01	123.99/11.17	98.15	67.43/5.56	83.10/9.38	76.49/5.49	75.67
44.5	10.8	62.45/12.44	110.68/18.83	136.58/16.36	103.24	66.73/5.57	82.99/8.76	81.83/6.79	77.18
44.5	21.5	70.57/7.08	125.12/17.99	132.39/11.51	109.36	72.72/5.80	99.51/16.23	92.86/14.66	88.36
62.8	4.2	64.10/8.85	78.42/11.73	83.25/8.76	75.26	67.20/8.27	83.33/8.49	71.89/6.68	74.14
62.8	8.4	65.56/10.67	92.24/11.10	112.08/15.88	89.96	65.91/9.02	78.73/11.29	78.52/7.94	74.39
62.8	10.8	70.12/7.27	96.47/13.14	118.20/7.35	94.93	68.53/6.21	80.86/7.32	79.61/7.40	76.33
62.8	21.5	83.96/12.98	106.70/16.40	130.26/10.67	106.98	67.47/12.97	83.46/5.34	94.72/10.75	81.88

Note: the surface roughness by layer is expressed as mean value / standard deviation.

Table 4. Surface roughness *Rz* (µm) by cutting mode, minimal and maximal values

Cutting speed (m/s)	Feed speed (m/min)	Surface roughness Rz (µm) Conventional cutting		Surface roughness Rz (µm) Climb cutting	
		Min	Max	Min	Max
44.5	4.2	76.20	101.06	61.14	72.32
44.5	8.4	90.62	105.04	68.18	84.68
44.5	10.8	92.27	117.23	68.63	85.20
44.5	21.5	99.15	120.10	77.81	100.92
62.8	4.2	61.50	86.27	68.92	81.01
62.8	8.4	81.09	97.34	60.32	87.27
62.8	10.8	87.24	101.94	68.30	85.83
62.8	21.5	93.87	121.44	68.01	94.30

Table 5 and 6 shows the results of sound pressure according to cutting mode for both cutting speeds and feed speed, including the idle emitted sound pressure, and minimal and maximal values as well.

Table 5. Sound pressure (*Pa²*) by cutting mode

Cutting speed (m/s)	Feed speed (m/min)	Sound pressure (Pa^2) Conventional cutting			Sound pressure (Pa^2) Climb cutting		
		Mean	St. deviation	Idle	Mean	St. deviation	Idle
44.5	4.2	1.02	0.19	0.11	0.97	0.07	0.12
44.5	8.4	1.31	0.17	0.11	1.19	0.12	0.12
44.5	10.8	1.21	0.09	0.12	1.48	0.12	0.10
44.5	21.5	2.38	0.16	0.13	2.47	0.21	0.12
62.8	4.2	1.71	0.09	1.17	2.92	0.21	1.31
62.8	8.4	2.15	0.36	1.07	2.71	0.31	0.92
62.8	10.8	2.15	0.36	1.25	2.68	0.28	1.37
62.8	21.5	2.83	0.31	1.28	3.48	0.39	1.18

Table 6. Sound pressure (*Pa²*) by cutting mode, minimal and maximal values

Cutting speed (m/s)	Feed speed (m/min)	Sound pressure (Pa^2) Conventional cutting		Sound pressure (Pa^2) Climb cutting	
		Min	Max	Min	Max
44.5	4.2	0.71	1.27	0.87	1.14
44.5	8.4	1.11	1.67	1.01	1.35
44.5	10.8	1.06	1.36	1.33	2.75
44.5	21.5	2.03	2.56	2.12	2.68
62.8	4.2	1.59	1.87	2.63	3.26
62.8	8.4	1.75	2.74	2.41	3.41
62.8	10.8	1.85	2.89	2.28	3.10
62.8	21.5	2.60	3.68	3.09	4.24

Figure 1 shows the results of surface roughness *Rz* (µm) for both levels of cutting speed: 44.5 and 62.8 (m/s), at different points of feed speed (m/min). The higher level of cutting speed (62.8 m/s) shows, at every point of feed speed, a less rough surface compared to 44.5 (m/s) of cutting speed, being the slowest feed speed (4 m/min) where the smoother surface is found (between 75 to 79 µm of *Rz* as mean value) for both cases of cutting speed, while the increase of feed speed produced a continuous surface degradation. However, non significant differences where found for surface roughness between both cutting speeds.

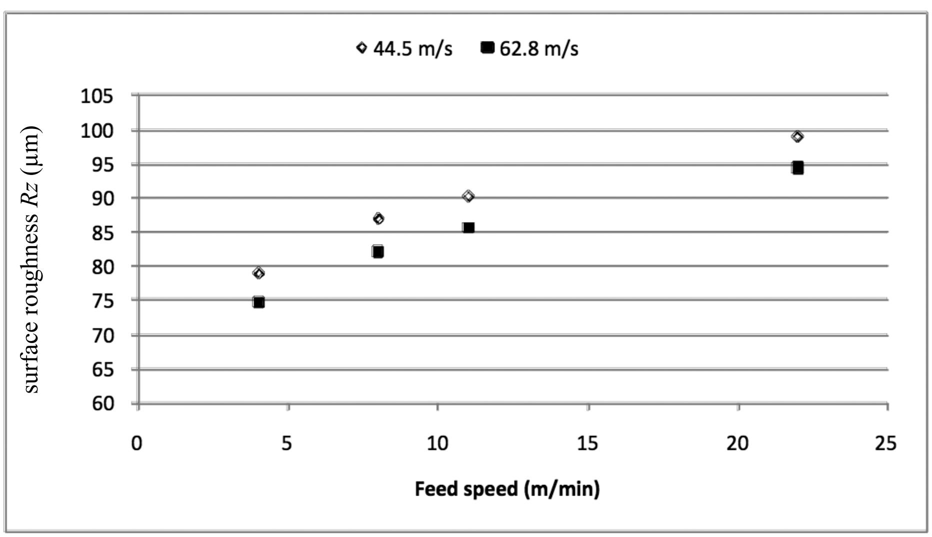

Fig 1. Cutting speed (m/s) influence on surface roughness *Rz* (µm) by feed speed

The same behaviour was found for sound pressure (Figure 2) and feed speed, since a high feed speed results in an increasing tendency of sound pressure as mean value; similar results were found by Iskra and Tanaka (2005) for a constant cutting speed, with a high level of correlation. Also, the higher level of cutting speed (62.8 m/s) shows that more sound pressure is produced during the process at every point of feed speed, ranging from 2.32 to 3.15 (Pa^2) of sound pressure as mean value (standard deviation 0.39), and from 1.00 to 2.43 of (Pa^2) for 44.5 (m/s) of cutting speed (standard deviation 0.21).

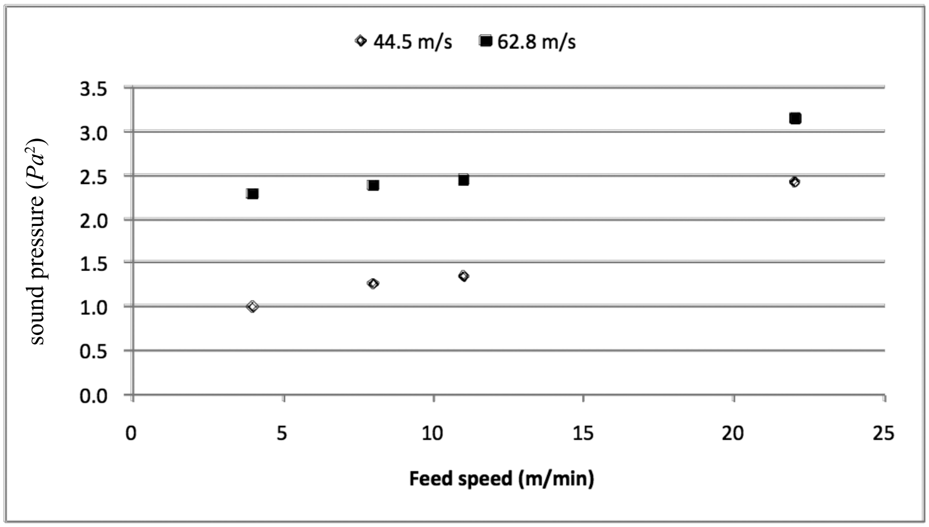

Fig 2. Cutting speed (m/s) influence on sound pressure (Pa^2) by feed speed

Therefore, these results show that feed speed affects both sound pressure and surface roughness, since the higher the feed rate, the greater the sound intensity and surface roughness generated.

The cutting mode and chip thickness effect on surface roughness and sound pressure

Figures 3 through 6 shows the findings for the relationship between surface roughness and sound pressure, considering the chip thickness on both cutting modes. In Figure 3 and 4, for the low cutting speed (44.5 m/s) and for both cutting modes, the finding shows a decrease of the surface quality with the increase of the chip thickness on the MDF profile (as mean values of the roughness across the profile). And for both cutting modes, the results are consistent with others studies (Aguilera 2010b; Aguilera and Martin 2001; Benardos and Vosniakos 2002; Mitchell and Lemaster 2002), where the smoother surface roughness is attained with the climb cutting mode rather than conventional cutting, with maximal values of 88 µm for climb and 109 µm for conventional cutting. Significant differences were found at 95% of confidence for surface roughness in both cutting modes.

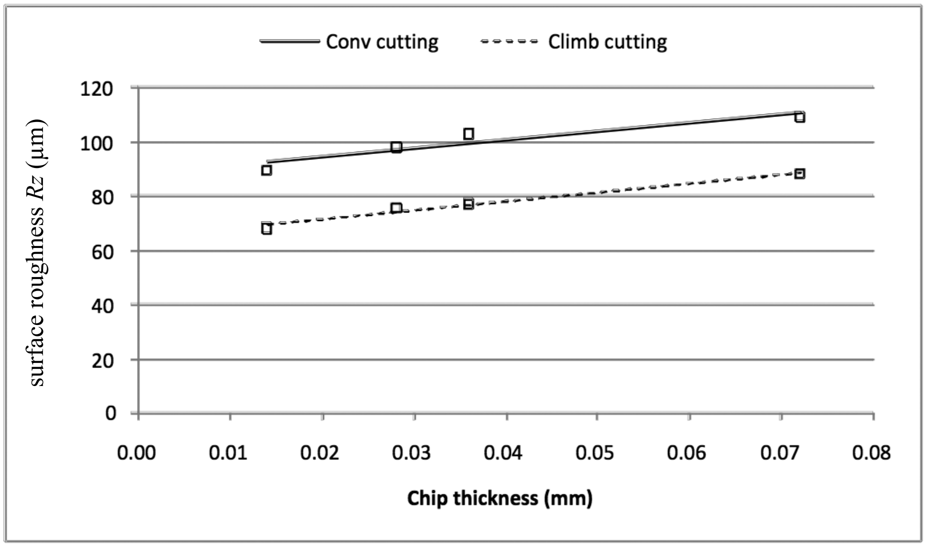

Fig 3. Surface roughness by chip thickness for conventional and climb cutting mode at 44.5 m/s of cutting speed

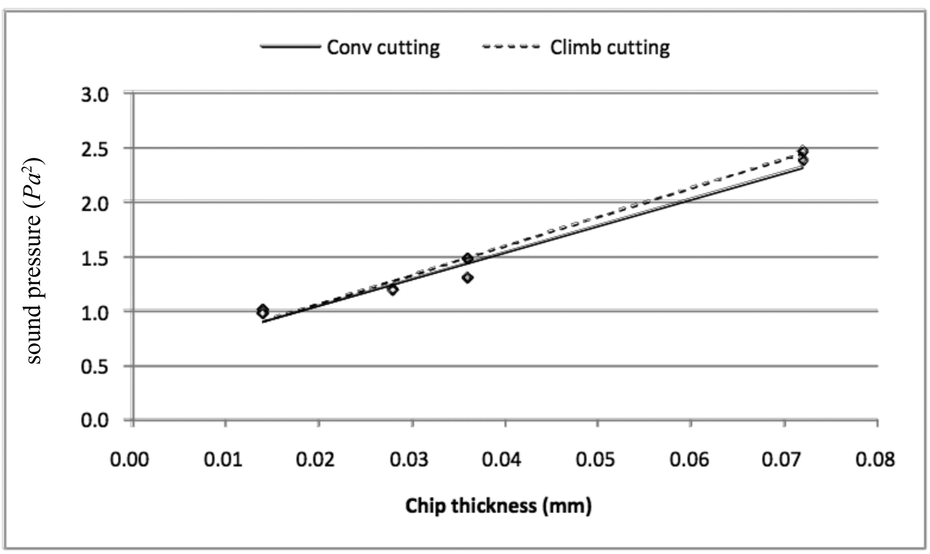

Fig 4. Sound pressure by chip thickness for conventional and climb cutting mode at 44.5 m/s of cutting speed

The similar trends were found for the measurement of sound pressure signals, where the increase of the chip thickness for both cutting modes was reflected by an increase of the sound pressure, but with no significant differences between conventional and climb cutting mode at higher level of chip thickness, where climb cutting reached 2.47 Pa^2 and conventional cutting 2.38 Pa^2, that is to say that more sound pressure was produced during the chip formation on climb cutting mode when a thick chip is generated at the beginning of the cut. Determination coefficient and linear regression equations for surface roughness – sound pressure are shown in Table 7.

Concerning 62.8 m/s of cutting speed, the findings are presented in Figure 5 and 6, where a similar behaviour is seen for those of lower cutting speed, a smoother surface roughness with the decrease of the chip thickness, and a reduced sound pressure as well. The best surface quality was reached on climb cutting mode at every level of chip thickness with a minimal value of 82 µm, and 88 µm for 44.5 m/s of cutting speed, being not significant the differences at low level of chip thickness, but significantly at higher level.

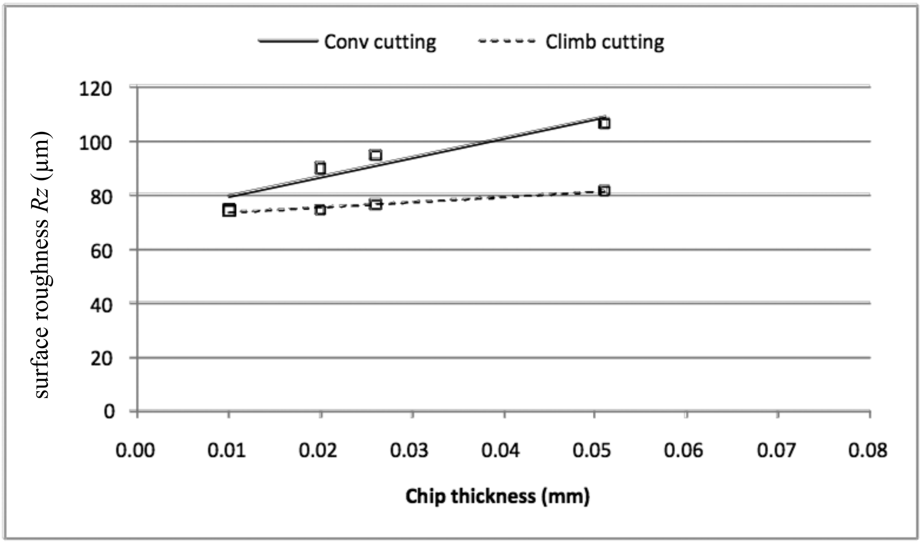

Fig 5. Surface roughness by chip thickness for conventional and climb cutting mode at 62.8 m/s of cutting speed

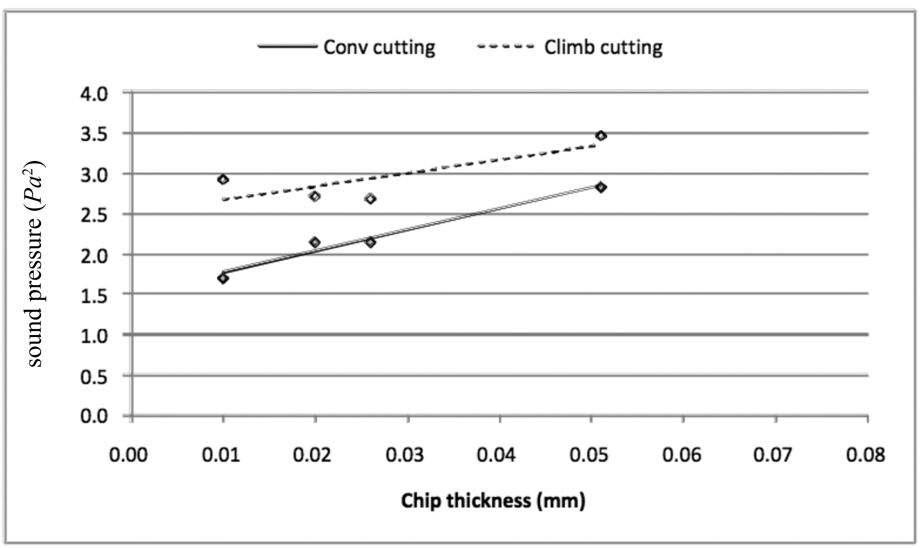

Fig 6. Sound pressure by chip thickness for conventional and climb cutting mode at 62.8 m/s of cutting speed

About the results of sound pressure measurements, a best differentiation was observed for 62.8 m/s of cutting speed between both cutting modes, where climb cutting mode generates more sound pressure reaching a maximal value of 3.48 Pa^2, and conventional cutting 2.83 Pa^2. Table 7 shows the determination coefficient and linear regression equations for both cutting speed and cutting modes. In all evaluated conditions a good level of correlation was obtained, being the chip thickness a good parameter that explains very well the variation of surface roughness, and is also a good predictor of the sound pressure.

Table 7. Determination coefficient and linear regression equations for surface roughness – sound pressure by cutting speed and cutting mode, dependent variable mean chip thickness

Cutting speed	Cutting mode	Equation	R^2
44.5	Conventional	$Rz = 316.05\ e + 88.24$	0.87
44.5	Climb	$Rz = 331.41\ e + 64.96$	0.98
62.8	Conventional	$Rz = 716.21\ e + 72.62$	0.91
62.8	Climb	$Rz = 201.64\ e + 71.29$	0.96
44.5	Conventional	$Pa^2 = 24.43\ e + 0.56$	0.97
44.5	Climb	$Pa^2 = 26.59\ e + 0.53$	0.99
62.8	Conventional	$Pa^2 = 26.08\ e + 1.51$	0.97
62.8	Climb	$Pa^2 = 16.42\ e + 2.51$	0.61

Note: cutting speed (m/s), *Rz* is surface roughness (µm), *e* is the mean chip thickness (mm), Pa^2 is the sound pressure ($Pascal^2$), R^2 determination coefficient

Analysis of variance

The analysis of variance (95% of confidence) for surface roughness on factorial experiment shows that all main effects: cutting mode (A), feed speed (B), cutting speed (C) and interactions cutting mode – feed speed, cutting mode – cutting speed and between the three main effects ABC are significant. The interaction between feed speed and cutting speed was no significant. The interaction cutting mode – feed speed implies that the differences between responses to the cutting mode vary with the level of the feed speed, where responses are measured over both cutting speed. The significant interaction of the three main effects ABC can be considered as an interaction AB with factor C (cutting speed), or the interaction AC with factor B (feed speed). In this case the significant AB interaction implies that there are significant differences at every point of feed speed for both levels of cutting mode. And for AC interaction, only at 44.5 m/s of cutting speed there are significant differences in surface roughness, nor for 62.8 m/s.

Following the same tendency as surface roughness, the analysis of variance for sound pressure shows that all main effects: cutting mode (A), feed speed (B), cutting speed (C) and interactions cutting mode – feed speed, cutting mode – cutting speed and between the three main effects ABC are significant. Similarly to surface roughness, non significant differences were found on the interaction between feed speed and cutting speed. Interaction cutting mode – feed speed results only in a significant difference for sound pressure at the low level of feed speed or chip thickness. For cutting mode – cutting speed interaction, both levels of cutting speed present significant differences in sound pressure.

CONCLUSIONS

The main conclusions of this research are that the sound pressure captured during the rip sawing of MDF was well correlated through the cutting process with the surface roughness, where the changes in feed rate are clearly detected, being the relationship linear and positive for both surface roughness and sound pressure. In same way, the increase of the cutting speed determines an improvement of the surface roughness and an increase of the sound pressure. The mean chip thickness demonstrates its close relationship with the surface roughness and sound pressure as well, with high determination coefficients, and then the chip thickness appears as a good element to assess accurately both response variables. The climb cutting mode permits to achieve the best surface quality with high levels of sound pressure than conventional cutting. Both cutting modes reach high correlation coefficients. The measurement of sound pressure signals, results in a useful tool to control the wood cutting processes, presenting a large potential to predict the surface roughness, and the effect of the change of cutting conditions on MDF rip sawing.

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