MEASURING CUTTING FORCES IN ROUTING WOOD AT VARIOUS GRAIN ANGLES
STUDY AND COMPARISON BETWEEN UP- AND DOWN-MILLING TECHNIQUES, PROCESSING DOUGLAS FIR AND OAK

Giacomo Goli[1], Rémy Marchal[2], Luca Uzielli[1], Martino Negri[3]

1. DISTAF University of Florence - 50145 Florence ITALY – giacomo.goli@unifi.it
luca.uzielli@unifi.it
2. ENSAM –LABOMAP – 71250 Cluny France – remy.marchal@cluny.ensam.fr
3. ITL/CNR 38010 S. Michele a/A Italy – negri@itl.tn.cnr.it

ABSTRACT

In the framework of a research dealing with surface quality and surface formation mechanics some specimens of Douglas fir and Oak have been routed at different grain angles with a 3-axis routing machine, with up- and down-milling techniques. Cutting forces have been measured by a tri-axial dynamometric platform, an interpretation of their behaviour is proposed and the different processes have been studied and compared.
The results of our study show the behaviour of parallel and normal force, as an influence of the grain angle, and give a geometrical explanation. Comparison of data from up- and down-milling shows how cutting forces are influenced by cutting geometry, and consequently the main differences between these two techniques. Data of Douglas fir and Oak are compared as well two different depths of cut for Douglas fir.

1. INTRODUCTION

In wood machining it is well known that the final quality depends on many factors. One of the main factors is the grain direction. In facts processing "with" or "against the grain" provides really different cutting conditions. The grain direction has an important role on the cutting mechanics because of the different mechanical properties of wood in the different sections. These interactions depend on many factors, "internal" or "external" to the wood. In our case every factor has been kept constant, in order to establish the role of the grain angle. A complete work of surface characterisation has been done, trying to understand the surface formation mechanics [Goli et al. 2002(7)], the surface final quality [Goli et al.2002(8)], the cutting forces and the chip formation and typology according to different milling techniques (-up and down-milling), wood species and cutting depths. A unifying approach to surface quality depending to the grain direction seems to be possible.

2. MATERIALS AND METHODS

2.1 The machining process

In order to define the best settings to process the specimens, some preliminary tests were performed. Douglas fir has been processed at different grain angles, with different depths of cut, feeding speeds and tool revolutions par minute. The specimens were equilibrated at an average moisture content of 13,2% for Douglas fir and 12,6% for Oak (see Table 2). The other parameters has been chosen in order to obtain a fast processing and a good final quality, with the available apparatus. We performed many tests processing “up-” and “down-milling”, in order to identify the most suitable technology and to analyse the cutting forces in the two processes, and a complete test has been conducted for Douglas fir (with a depth of cut of 0,5 mm and 1,5 mm) and Oak. After some investigations the set-up reported in Table 1 has been chosen.

Parameters imposed	**Cutting parameters**
Wood species: Douglas Fir (*Pseudotsuga Menziesii* Fr. Var. Menziesii) and Oak (*Quercus petrea*)	Cutting technology: up- and down milling
Milling machine: 3 axes CNC router	Cutting length: 80 mm
Rake angle (α): 20°	Cutting height: 30 mm
Clearance angle (β): 15°	Feeding speed: 5 m/min
Inserts on the cutting head: 2	R.P.M.: 13867 Rev./min
Inserts material: tungsten carbide screwed inserts(HW)	
Head diameter: 40 mm	

Table 1: experimental set-up adopted for the tests

Species characteristics	**Douglas fir**	**Oak**
Wood moisture content:	13,2% ~	12,6%~
Average specific gravity:	0,43 g/cm^3	0,66 g/cm^3
Cutting depth:	0,5 - 1,5 mm	0,5 mm

Table 2: experimental set-up adopted for the tests

The length of the specimen has been chosen in order to be held within the dynamometric platform borders, and its height in function of the tool edge length. The cutting depth has been chosen in 0,5 and 1,5 mm for Douglas fir and in 0,5 mm for Oak. The wood was shaped in order to avoid a contact with the top of the tool (only lateral contact), to avoid undesired disturbances in the measures. The specimen is held upon the dynamometric platform by two screws and a metal plate compressing itself. The dynamometric platform is fixed by four screws on a rectified steel plate, tightly held to the machine table by a vacuum system. The weight of the whole system was enough to keep it stable, and the vacuum system held it stiffly against the machine table. The grain angle (ξ) were changed from 0 to 90° with progressive increments of 10°. The use of the “-” before the angle value means that the surface has been processed “against the grain direction” otherwise the surface has been processed “with the grain”. The presence of “0” and “-0” and of “90” and “-90” means that the same surface has been processed after being tilted by 180°. This, i.e. processing in the two opposite directions, was done in order to verify the suitability of the measure, that in both cases should have the same value. We used specimens with annual rings oriented so that a radial face is processed, in order to avoid the alternating of early- and late-wood, consequently the surface quality results from processing early- and late-wood separately, with no interaction between the two, and cutting forces will not be affected by their alternation.

2.2 Cutting forces measurement and acquisition

The measurement of cutting forces during a routing process is a quite complicate operation because of the high frequency and the periodical solicitation that excite the system to vibrate according to its natural frequency. Moreover a machine with more axis produce lots of vibrations affecting the signal. For this reason we reduced as much as possible the mass handing over the platform. The measuring system is a tri-axial dynamometric piezoelectric platform, connected to three charge amplifiers switched to “long” modality. We measured cutting forces along the tree axes, therefore only two of them (X and Y) are analysed in this paper. Data have been collected, stored and analysed by an acquisition board and the means of the computer analysis. The set up is reported in Table 3.

Measuring system	Tri-axial dynamometric piezoelectric platform
Platform cut-off frequency	3000 Hz
Acquisition device	Computer board
Anti alias filter	Mechanical
Sampling frequency	10.000 Hz

Table 3: Acquisition system set-up

The forces are oriented as follows: the "parallel force" is oriented along the feeding direction and has its positive versus in the cutting direction; the "normal force" is oriented perpendicularly to the feeding direction and its verse is positive going inside the surface. Both parallel and normal force are in the same horizontal plane.

2.3 Cutting forces analysis

The measurement of cutting forces during processing is always difficult, because of the interferences brought by all the vibrations affecting the system. The signal is often difficult to analyse, and to retrieve cutting forces is a really complicate operation. For this reason it has been necessary to operate an important filtering. By a side filtering very much would affect the data, but at the same time would clean them from useless noise. Even if filtered data do not represent exactly cutting forces, they are easy to analyse and to process and not far from real cutting forces (anyway closer than with noise).
For this reason a filter type Butterworth of 4th order set as low-pass at 500 Hz, has been used to clean the data from noise. Considering that 500 Hz is bigger than cutting frequency (462 Hz) we should not significantly affect the signal, and the embedded data. The cutting conditions are reported in Table 4

Cutting head revolution frequency	231 Hz
Time to make a revolution	0,0043 sec
Cutting frequency (2 edges)	462 Hz
Time between two chips	0,0022 sec

Table 4: System periodicity

and the analysis condition are set in Table 5.

Filter Frequency	500 Hz
Order	4^{th}
Type	Low-pass

Table 5: Analysis conditions

The domain analysed is always the time and we use the normal time-intensity graph and the autocorrelation function (autocorrelation is a function that allow us to retrieve the periodicity of a system).
Here follows some examples of the collected data and of the performed analysis. On the X axis for both signals is reported the "Time", while on the Y axis directly the force in "Newton" for time-intensity analysis, and an index going from 1 to –1 (1: perfectly correlated, -1: anti-correlated) for the autocorrelation function.
The first test we have done is to verify the absence of noise while the machine was moving but not processing (see Figures 1 – 2). In the graphs the X has to be red as "normal force" and the Y as "parallel force".

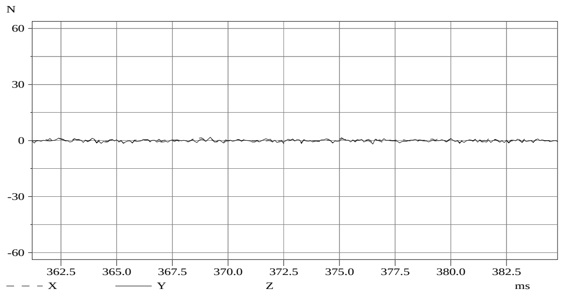


Figure 1*: Non filtered signal while the machine is moving without processing wood (idle).*

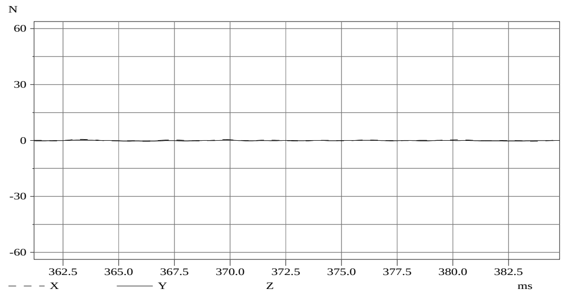


Figure 2*:Filtered signal while the machine is moving without processing wood (idle).*

Once verified the absence of significant noise, we began the analysis of the signals acquired while processing. The filtered and non filtered signals look like in Figure 3 – 4. As can be easily seen, valleys have a slightly different value in the two cases (filtered and non-filtered), but if the non-filtered signal contains the information we are seeking, it has too much noise to be clearly red. Filtered signal, even if not exactly representing the cutting forces, is very well correlated to them. For this reason we have chosen to analyse this one.

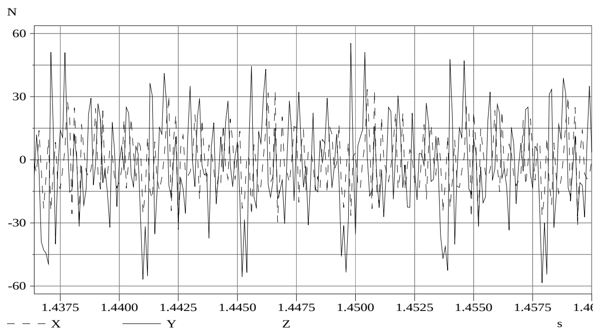


Figure 3*: Non filtered signal while the machine is moving and processing a specimen with ξ 20°.*

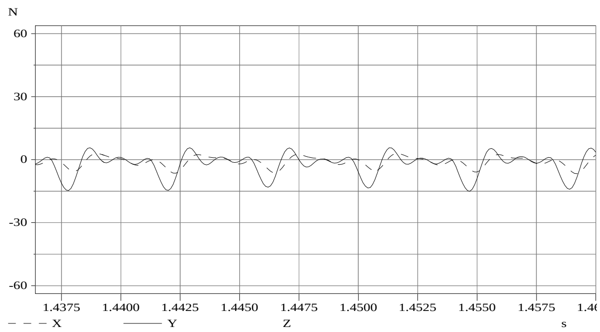


Figure 4*: Filtered signal while the machine is moving and processing a specimen with ξ 20°.*

The analysis of the autocorrelation function while the machine is moving but not processing doesn't show any particular periodicity, while processing we can easily see the periodicity of the function. The distance of the first peak from the zero is 0,0043 sec., exactly the time necessary for a revolution (see Figures 5 – 6).

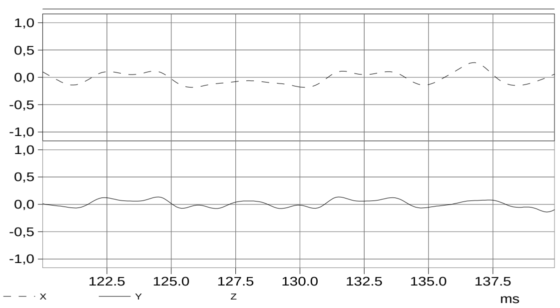


Figure 5: *Autocorrelation of filtered signal while the machine is moving but not processing.*

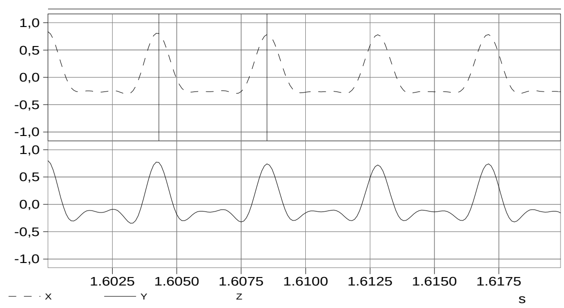


Figure 6: *Autocorrelation of filtered signal while the machine is processing a specimen with ξ 20°.*

Here follows a deeper analysis of time and autocorrelation functions for a specimen processed in the grain direction with a grain angle of 60°.
The acquired signals, in the time domain, change of intensity depending on the grain direction, but the shapes are very near (see Figure 7). As expected the main force is the "parallel force (represented as Y). By this plot appears manifest the periodicity of the function. The time elapsed in a cycle (represented by the cursors position) was measured in 0,0043 sec., it means that every cycle in the graph corresponds to a revolution of the tool. In our process we have two tools involved, and it means that a tool does not cut. As known when more than one edge is involved in the cut, one cuts more than the others, but in this case the cutting of the second edge is not visible at all.

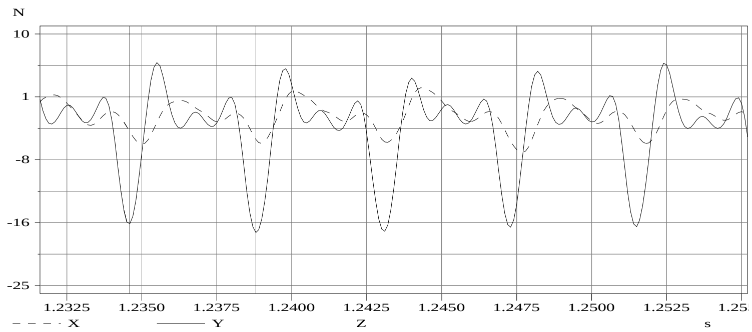


Figure 7: *Filtered signal while the machine is processing at ξ 60°.*

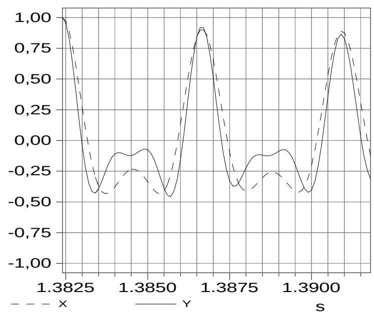


Figure 8: *Autocorrelation of filtered signal, processing at ξ 60*

To determine the cutting forces during the process, we measured the deepest valley consequent of an impact in the filtered signal. We have done 15 measurements, and after we have done an average to determine the cutting forces. This operation is possible because of the extreme regularity of the signals, as can be seen from the Standard Deviation reported in Table 6.

Standard deviation	0	10	20	30	40	50	60	70	80	90
X axis - up-mill - with the grain	0,6	0,7	0,7	2	0,9	1,8	0,8	0,5	1,0	1,7
Y axis - up-mill - against the grain	0,3	0,6	0,9	0,7	0,7	0,7	0,5	1,0	0,5	0,9
X axis - down-mill - with the grain	0,4	1,0	0,4	1,5	0,6	1,1	1,8	0,2	0,4	0,8
Y axis - down-mill - against the grain	0,4	0,4	0,6	0,3	0,4	0,4	0,5	0,9	1,2	0,4

Table 6: Standard deviation in measured cutting forces

3. RESULTS

General results has been drawn about up- and down-milling techniques, analysing the cutting forces measured for Douglas fir processed with 0,5 mm of depth of cut. These results have been compared with the results obtained processing Douglas fir with a depth of cut of 1,5 mm and Oak with a depth of cut of 0,5 mm. Finally all the data are observed and analysed together. In the graphs were grain angle is reported from 0° until 90° it is marked if the data concern the forces processing “with the grain” or “against the grain” (0/90 graphs). For the graphs going from -90 to 90 the negative angle concerns the values measured processing against the grain, while the positive-one concerns the data obtained processing with the grain. The 0 means that the specimen has been processed at straight grain.

3.1 Processing up-milling

With this technique the main points are that the blade moves upward during the cut and that the blade while processing moves in the direction where the surface have yet to be processed (down milling is the contrary) beginning to cut the chip from the thinner part. As first we can remark that the parallel force is always increasing from 0° until 90°, while for the normal force we can see some non linear evolutions. Moreover we can observe that the parallel force (as expected) is always bigger than the normal force and this one is always bigger processing with the grain than against the grain. This behaviour is because processing in the grain direction the tool exert a cross-compression that makes the cut harder. Processing against the grain in general produce cross-tension that leads to an easier cut. For the variations in the normal force, studying geometrically the problem we can calculate some significant angles in the process. Processing in the gain direction “20°” is an important angle because the grain direction is perpendicular to the rake face. This should lead to an increase of cutting forces because as explained the cut is harder if exerted for cross-compression. Processing against the grain an important angle is “-70°” because the grain is parallel to the rake face leading to a cutting forces decrease because the cut (often the chip processing against the grain is not cut but broken) happens for cross-tension. These two theoretical angles should vary of some degrees because the maximal force is not exerted in the point of tangency between the surface and the tool but after that the cut has began and the chip has increased his thickness. These two points can be easily seen observing the normal force behaviour in figure 7 where the maximum processing with the grain is at 30°, while the minimum processing against the grain is located at -70. The same data are plotted in Figures 9 and 10.

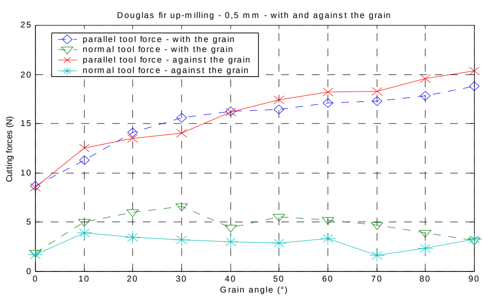


Figure 9: 0/90 diagram of cutting forces up-milling Douglas fir with 0,5 mm of depth of cut.

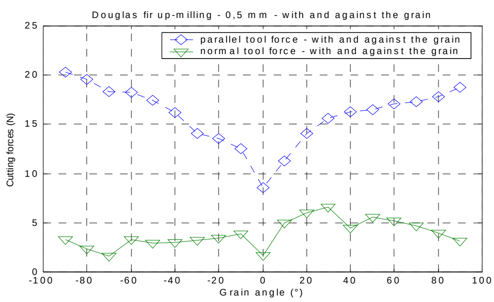


Figure 10: -90/90 diagram of cutting forces up-milling Douglas fir with 0,5 mm of depth of cut.

3.2 Processing down-milling

With this technique the main points are that during the cut the blade moves downward and in the direction where the surface have already been processed, beginning to cut the chip from the thicker part. With this technique for both parallel and normal force we can see some non linear evolutions changing the grain direction. Moreover we can say that the parallel force (as expected) is always bigger than the normal force and this one is always bigger processing with the grain than against the grain. This behaviour can be explained as for up milling technique. For the variations in the force magnitude we can give the same explanations given for up-milling but everything is transposed of -20° (the maximum in 30° up-milling down-milling is at 10°, and the minimum in -70° up-milling, down-milling is in -90°), the reasons will be explained in the next paragraph. The same data are plotted in figures 11 and 12.

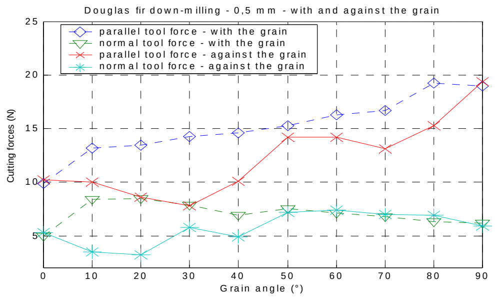


Figure 11: 0/90 diagram of cutting forces down-milling Douglas fir with 0,5 mm of depth of cut.

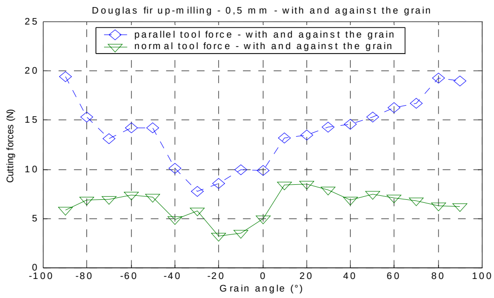


Figure 12: -90/90 diagram of cutting forces down-milling Douglas fir with 0,5 mm of depth of cut.

The great slope in parallel force processing down milling is because of the presence of a particular defect, called tilted grain by the authors (see figure 14). In this defect wood layers are broken for cross-tension and tilted. The normal force, as the parallel one are low because as well known wood cross-tension properties are very week.

3.3 Comparison between processing up- and down milling

Comparing up- and down-milling (see Figure 13) we can easily observe that processing with the grain, the parallel force shows values that are very close, while processing against the grain the down-milling values are in general lower than those measured up-milling. This is because of the cited defect "tilted grain" that set up only with down-milling technique. About the normal force we can see that down-milling is always higher than up milling, this is because with the down-milling technique the cut starts from the thicker part and the motion is downward. A very important particular to note is that the shapes of up- and down-milling diagrams are very similar, but for the down milling forces the diagrams are shifted 20° on the left. This is explainable by the different geometry cutting up and down milling. The different cutting geometry (upward and downward motions) results in a different evolution of the angle between the grain direction and the rake face, that only in the tangent point with the new surface results to be the same (see Figure 15).

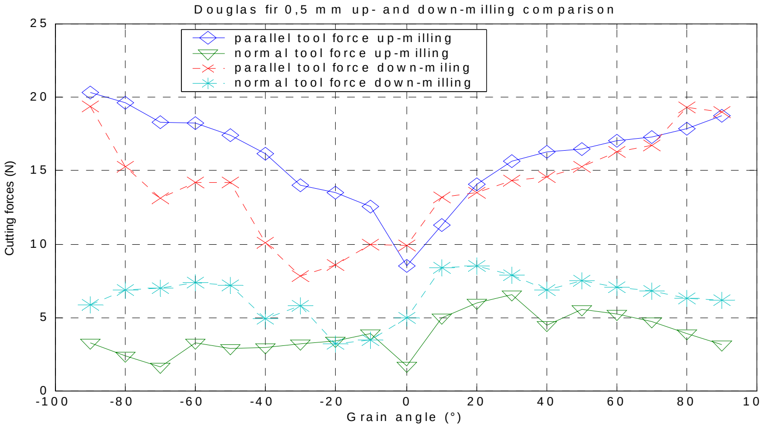
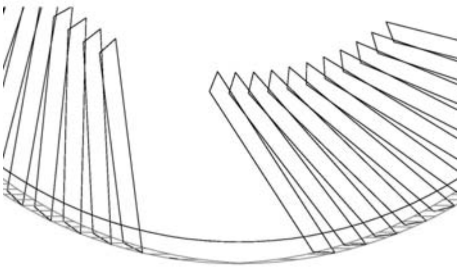


Figure 13: -90/90 diagram of cutting forces up- and down-milling Douglas fir with 0,5 mm of depth of cut.

Figure 14: the defect called "tilted grain".

As shown in figure 16 (the image is in scale with the real process) an angle of 20° is held between the impact point processing down-milling and the getting out of the edge processing up-milling with a cutting depth of 0,5 mm (the angle between the two points is 22°). Probably in this point the chip is thick enough to oppose a reaction, and this difference shifts the down milling diagrams of -20° as regards up milling ones because of the difference in relative orientation between the rake face and the grain direction.



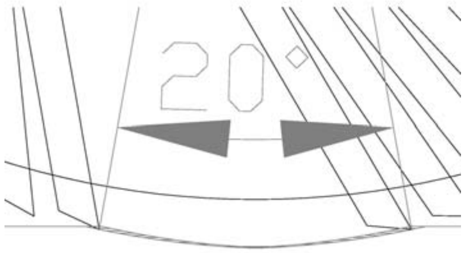
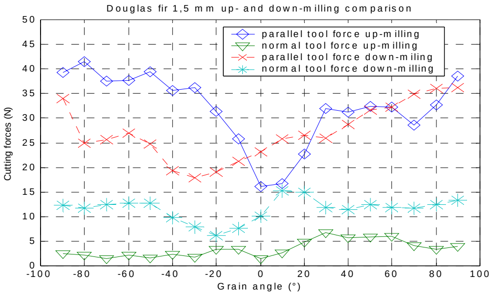


Figure 15: changing of the angle between the rake face and the grain direction processing up- and down milling with the same grain direction

Figure 16: changing of the angle between the rake face and the grain direction processing up- and down-milling with the same grain direction

The same thing can be observed in Douglas fir processed at 1,5 mm of depth of cut (see figure 17) and Oak processed at a depth of cut of 0,5 mm (see figure 18) where the differences are connected to the formation of tilted grain. This proves that the same mechanical reactions are engaged in the processes and that cutting forces are strictly connected with the grain direction.



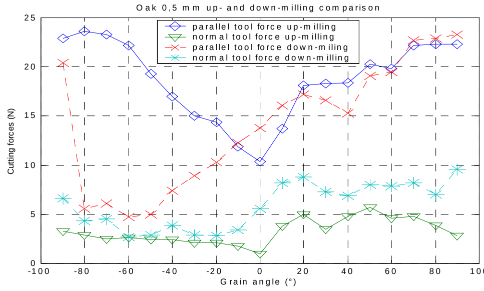


Figure 17: -90/90 diagram of cutting forces up- and down-milling Douglas fir with 1,5 mm of depth of cut.

Figure 18: -90/90 diagram of cutting forces up- and down-milling Oak with 0,5 mm of depth of cut.

3.4 Up- and down-milling Douglas fir at different depths of cut

Processing the same species with different depths of cut (Douglas fir processed at 0,5 mm and 1,5 mm) we can observe different values as magnitude but the shape of the curves remains the same (see figure 19). As known the resultant of the cutting forces increase with the chip thickness, but as shown the single components increase in a different way. The normal force processing up-milling at 0,5 and 1,5 mm does not increases significantly, while processing down-milling it increases of about 100%. A very significant rise in the values is for the parallel force processing up-milling, proving that with this technique the mechanics are mainly depending on the parallel force, while down-milling both have an important role because of the downward motion pushing the wood on the surface.

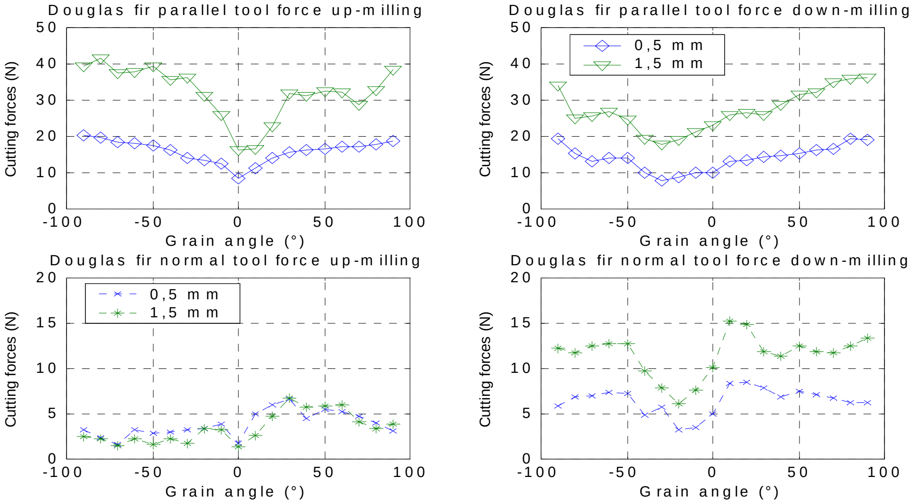


Figure 19: -90/90 diagram of cutting forces up- and down-milling Douglas fir with 0,5 and 1,5 mm of depth of cut.

3.5 Up- and down-milling different species

Up- and down-milling different species (Douglas fir and Oak) with the same depth of cut (0,5 mm) we can observe that the values are not very different. The parallel force processing up- and down-milling is bigger for Oak (with the exception of down milling against the grain because of the formation of tilted grain), while the normal force is bigger for the Douglas fir (probably for the highest friction coefficient). These results depends even on the moisture content, measured 13,2% for Douglas fir and 12,6% for Oak. Moisture content have an important influence on wood mechanical properties. In this case the higher moisture content in Douglas fir probably involve a higher friction coefficient, while the lower moisture content in Oak involve a higher stiffness that probably makes the cut easier (see figure 20).

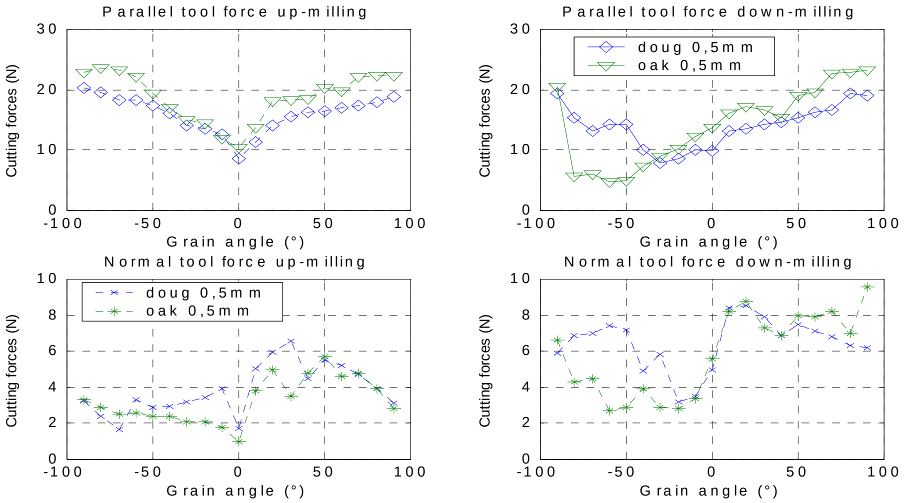


Figure 20: -90/90 diagram of cutting forces up- and down-milling Douglas fir and Oak with 0,5 mm of depth of cut.

All the data are shown together (plotted for up- and down-milling technique and for principal and normal force) in Figure 21.

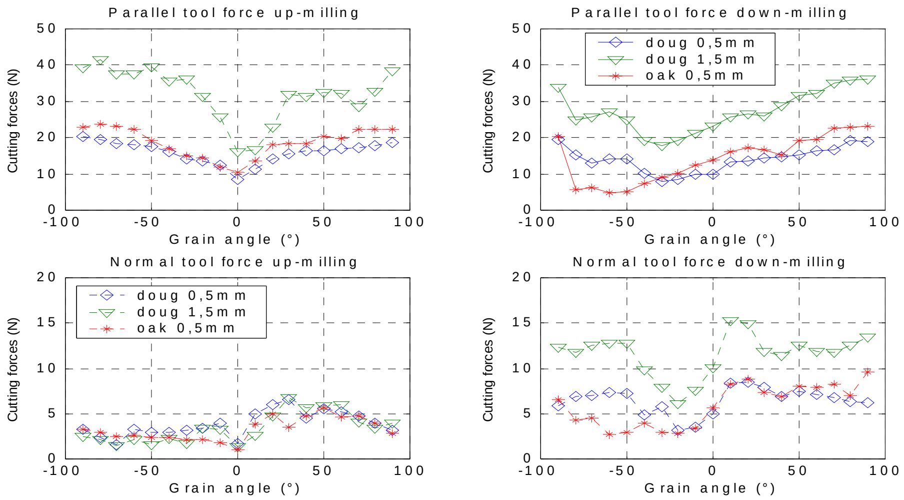


Figure 21: -90/90 diagram of cutting forces up- and down-milling Douglas fir with 0,5 and 1,5 mm of depth of cut and Oak with 0,5 mm of depth of cut.

4. CONCLUSIONS

In conclusion a method for analysing cutting forces during a milling process has been developed. This method has been verified processing the same species at different depths of cut and different species with the same depth of cut. Up- and down-milling techniques has been severally analysed and compared together. The two processes have been discussed by a geometrical point of view and this analysis has been connected with cutting forces measurements. Processing up-milling some significant grain angles have been find. This angles correspond to the perpendicularity between the rake face and the grain angle (20°) and to the parallelism between the two (-70°). These are special situations because processing in perpendicularity means that the cut is happening for cross-compression making the cut difficult (this should maximise cutting forces) and in parallelism by transverse tension making the cut easier (this should minimise cutting forces). This behaviour has been confirmed by the cutting forces measurement and analysis. In the normal force, processing up milling at 30° and -70° we can find the minimum and the maximum. The parallel force increase continuously from 0° until 90° and from 0° until -90°. Processing down-milling the diagrams are very similar but shifted of -20° as regards up-milling. A geometrical explanation has been proposed, in facts covering the same arc of a circle in the chip cutting due to the upward and downward motion the angle between the rake face and the grain is not the same. In our case from the impact point down-milling (greatest thickness in the chip and maximum cutting forces) and the getting out point up-milling (greatest thickness in the chip and maximum cutting forces) there is a difference of 22° that explains this behaviour. When down-milling, the normal force is always bigger than up-milling because of the greater chip thickness at the impact and because of the downward motion. In general we can say that down-milling technique requires more force than up-milling technique. Parallel force down-milling against the grain is usually lower because of the formation of "tilted grain". Processing Douglas fir at different depths of cut we can observe an increase of the cutting forces. Up-milling this increment is very important for the parallel force, while the normal force doesn't rise significantly. Down-milling both the forces rise up significantly. Processing Douglas fir and Oak with the same depth of cut we didn't observe significant differences in the cutting forces values, the parallel force is always bigger processing Oak with the exception of down-milling against the grain because of the more larger presence of tilted grain.

5. REFERENCES

1. **Cyra G.**, **Tanaka C.** – The effects of wood-fiber directions on acoustic emission in routing, Wood Science and Technology 34 (2000) 237-252.
2. **Koch P.** – Utilization of the southern pines Vol. II, U.S. Department of Agriculture-Forest Service.
3. **McKenzie W. M.** – Wood is easy to cut - or is it?, 11th International Wood Machinng Seminar proceedings 27-39.
4. **Stewart H. A.** – Effect of cutting direction with respect to grain angle on the quality of machined surface, tool force components, and cutting friction coefficient, Forest Product Journal Vol. 19 No. 3 pag. 43-46.
5. **Giordano G.** – Tecnologia del Legno Vol. II, UTET.
6. **Loehnertz S. P., Vazquez Cooz I.** – Sawtooth Forces in Cutting Tropical Hardwoods Native to South America, Forest Products Laboratory, Research Paper FPL-RP-567 (1998).
7. **Goli G., Bleron L., Marchal R., Uzielli L., Negri M.** 2002 (1)- Measurement of cutting forces, in moulding wood at various grain angles. Initials results with Douglas Fir. Proceedings of the Conference: Wood science and engineering in the third millennium – Brasov (RO) – November 17-18th 2002.
8. **Goli G., Bleron L., Marchal R., Uzielli L., Negri M.** 2002 (2)- Surfaces formation and quality in moulding wood at various grain angles. Initial results with Douglas fir and Oak, Proceedings of the IUFRO Symposium: Wood Structure and Properties 2002 – Zvolen(SK) September 1-3rd 2002.