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EDITION

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# PROCEEDINGS

UNIVERSITATEA TRANSILVANIA BRASOV

TRANSILVANIA University of Brasov- ROMANIA Faculty of Wood Industry

# MEASUREMENT OF CUTTING FORCES, IN ROUTING WOOD AT VARIOUS GRAIN ANGLES. INITIAL RESULTS WITH DOUGLAS-FIR.

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***Abstract:*** *In the framework of a research dealing with quality of machined wood surfaces and analysis of their formation process, some tests have been done on Douglas-fir specimens, in order to study the cutting forces and the surface formation mechanics at different grain angles, processing against and along the grain direction. Surfaces have been analysed by macroscopic observation and by profile analysis. Cutting forces have been measured to understand mechanisms of surface formation for different grain angles.*

*Key words: surface quality, grain angles, cutting forces, profiles measurements, Douglas fir.*

## 1. INTRODUCTION

When machining Douglas fir wood, it is difficult to obtain a good surface quality, because of the significant differences between early- and late-wood. Many effort has been made in the recent years in order to understand Douglas fir most convenient processing settings and consequently to obtain good surface quality. This work were undertaken in order to clarify the mechanics involved in the chip and surface formation when machining Douglas fir and other wood species, as a function of the cutting geometry resulting from different grain orientations of the wood. In facts the final surface quality is influenced by many "external" factors, such as the tool settings or the tool material, and by some factors "internal" to the wood, such as moisture content, and mainly grain angle. The available technologies should allow us to adjust the external factors so that the best quality can be obtained, compatibly with the internal factors. If the internal factors are far from the optimum for processing, technologies might improve the final quality, but a good quality will never be achieved. To summarise this concept we may say that a piece can be profitably processed by changing the external factors, only if the internal factors, and mainly the grain orientation, allow it. Therefore our research deals with the surface formation process, including measurement of cutting forces and classification of surface quality; however this paper focuses on the cutting process and cutting forces interpretation.

## 2. MATERIAL 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, moisture contents and tool revolutions par minute. For technical reasons the specimens were equilibrated at an average moisture content of 13,5%. 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. In this paper we consider only the up-milling technique, which showed to be the more suitable for processing solid wood. After some investigations the set-up reported in ***Table 1*** has been chosen.

| Fixed Parameters (imposed by the available materials) | Variables |
|---|---|
| Milling machine: 3 axes CNC router | Cutting length: 80 mm |
| Wood species: Douglas Fir (*Pseudotsuga Menziesii Fr. Var. Menziesii*) | Cutting height: 30 mm |
| Wood moisture content: 13,5% ~ | Cutting depth: 0,5 mm |
| Average specific gravity: 0,43 g/cm$^3$ | Feeding speed: 5 m/min |
| Rake angle (α): 20° | R.P.M.: 13867 Rev./min |
| Clearance angle (β): 15° | Cutting technology: up milling |
| Knives mounted on the cutting head: 2 | |
| Knives material: tungsten carbide screwed inserts(HW) | |
| Head diameter: 40 mm | |

*Table 1: experimental set-up adopted for the tests*

The length of the specimen has been chosen in order to keep it inside the borders of the dynamometric platform, so that a sharp measurement of cutting forces could be obtained; their height has been chosen in function of the tool height. The cutting depth has been chosen in 0,5 mm because with greater depths the surface quality didn't change significantly, and because the following processed surfaces were very close to the previous one. The wood was prepared in order to be cut only by the lateral knives, to avoid undesired disturbances when measuring the cutting forces. 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 large 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. 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 if the fibers were really perpendicular (for grain angle -90 and 90°) or parallel (for -0 e 0) to the processing plane: obtaining the same final quality, the same profile and the same cutting forces respectively for 0/-0 and 90/-90 proves that these parameters change with the grain direction, but are repeatable for the same direction. 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. See ***Figure 1***.

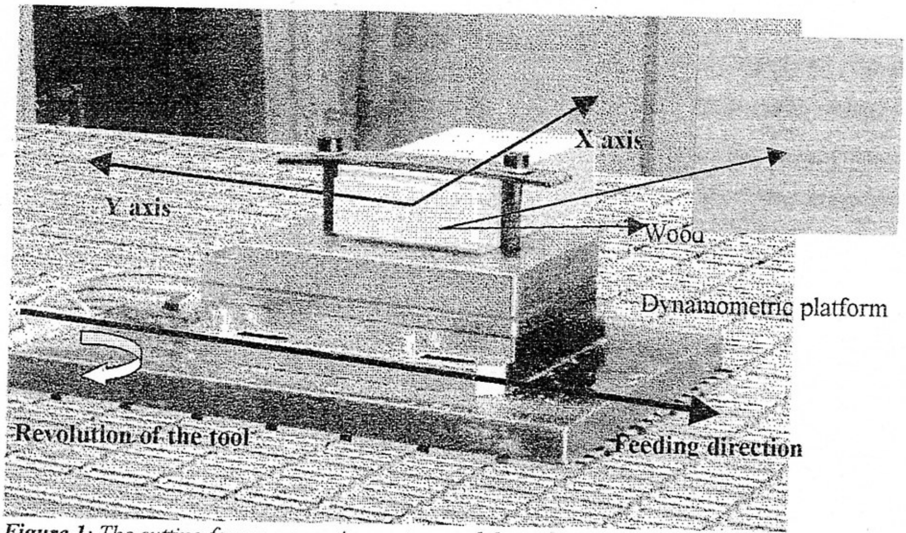


***Figure 1****: The cutting forces measuring system, and the processing settings.*

2.2 Cutting forces measurement, acquisition and analysis

The measurement of cutting forces during a routing process is not easy; 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) have been 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 2***.

| | |
|---|---|
| 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 2****: Acquisition system set-up*

The analysed forces are oriented as follows (see ***Figure 1***):

- Y is the main force, oriented along the feeding direction
- X (normal force) is oriented perpendicular to the feeding direction

Both X and Y are in the same horizontal plane.

2.3 Measurement of profiles

Profiles have been measured and analysed to give a more easy, effective and objective way for comparing the processed surfaces. In facts by other way it is difficult to make a comparisons, and for the surfaces processed at high moisture content it is difficult to find references for visual grading in the standards. For these reasons profiles have been measured and compared. The set-up used in the measurements is described in ***Table 3***.

| | |
|---|---|
| Device | 2D Profilometer |
| Sensor | Stylus |
| Measurement type | 2D |
| Stylus tip radius | 10 μm |

| | |
|---|---|
| Transducer's range | +/- 5 mm |
| Measuring length | 25 mm |
| Measuring speed | 1 mm/sec |
| Shape filter | Linear |
| Acquired parameters | Pa, Pt |

*Table 3: Profile measurement system set-up*

Pa is the integral of the profile divided by the profile length; **Pt** is the difference between the highest peak and the deepest valley in the profile length.

## 3. RESULTS

### 3.1 Surface quality

Surface quality is not deeply examined in this paper, we would just give a general idea of the quality by the means of some images and some profiles.

#### 3.1.1 Visual analysis

Her follows a brief photographic gallery concerning the processed surfaces (see ***Figures 2..9***).

***Figure 2:*** *ξ 0°, due to high moisture content, the surface presents some fuzzy grain in the early-wood*

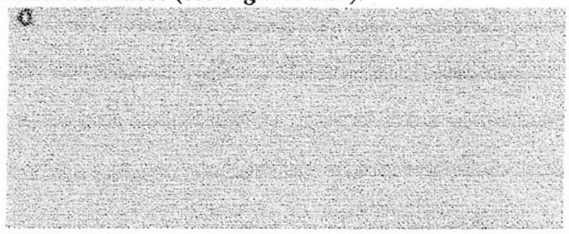

***Figure 3:*** *ξ -0°, due to high moisture content the surface presents some fuzzy grain in the early-wood*

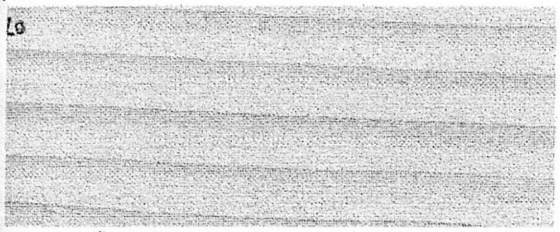

***Figure 4:*** *ξ 20, the surface has a good quality*

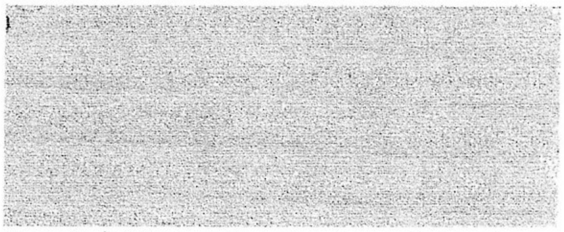

***Figure 5:*** *ξ -20°, the surface presents some fuzzy grain. The problems concern early and late-wood*

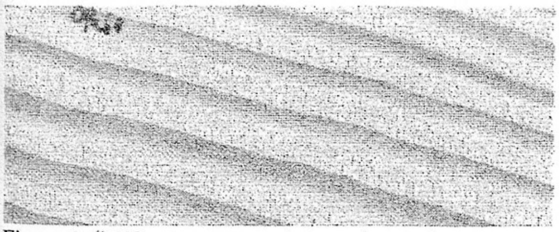

***Figure 6:*** *ξ 60°, some torn grain in early-wood.*

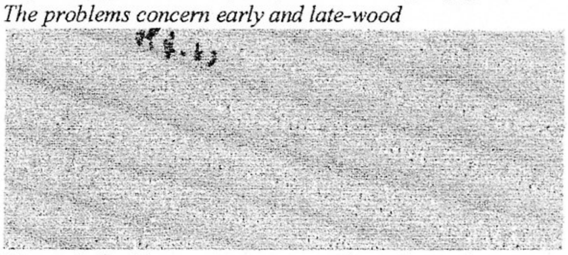

***Figure 7:*** *ξ -60, some torn grain in the early wood. Late wood is a little bit better*

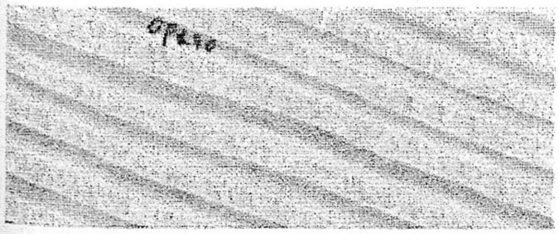

***Figure 8:*** *ξ 90°, early-wood is completely torn away*

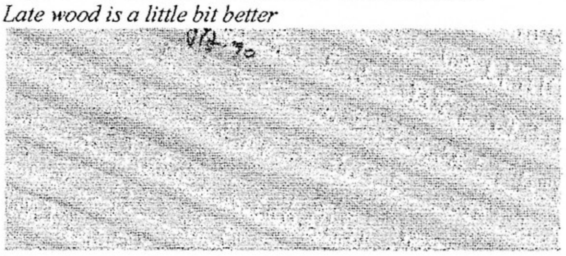

***Figure 9:*** *ξ -90°,early-wood is completely torn away*

We reported in this gallery the most meaningful images concerning the typical defects affecting the processed surfaces. Surfaces processed at straight grain (0 and -0) present some fuzzy grain due to the high viscosity of the early-wood, that causes the formation of this defect (the high viscosity is due to the high moisture content, for lowest moisture contents processing at 0/-0 carries a good final quality). At normal moisture content this defect arises processing against the grain with narrow grain angles. Processing along the grain direction, with narrow angles the surface final quality is good, while processing against the grain the surface presents some defects, typically "fuzzy-grain". For biggest angles (60, -60) the typical defect is torn grain, but its formation process is different between processing "against" and "along" the grain direction. At 90 and -90° early-wood is completely torn away in both case. It is easy by these photographs to remark the large difference between early and late-wood. An important point confirming the repeatability of the tests is the same aspect of the surfaces 0, -0 and 90, -90.

3.1.2 Profile analysis

If visual analysis allows us to have a general idea of the cutting mechanics, profile analysis is a very useful tool for comparison. For Douglas fir the evolution of the surface, changing the grain angles, is manifest. For the surface analysis and comparison we chose the primary profile. In facts roughness and waviness analysis are not necessary when the profile characteristics are so manifest, because of the difficult to correctly set the filtering. For these reasons we decided to use the primary profile, acquiring Pa and Pt (see ***Figure 10***).

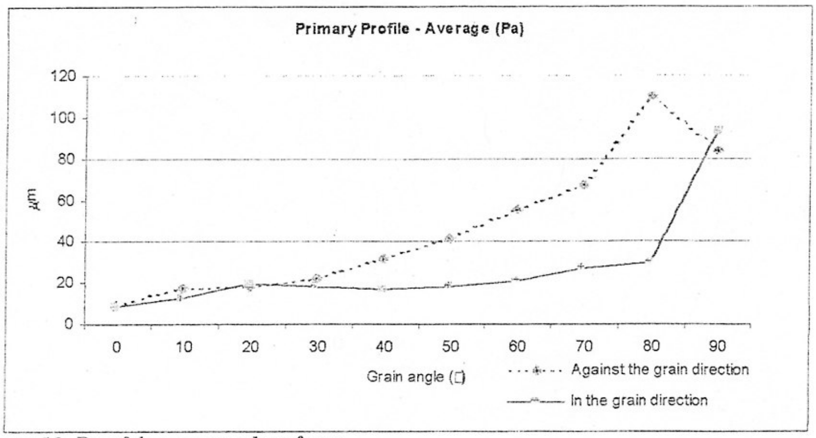


***Figure 10****: Pa of the processed surfaces*

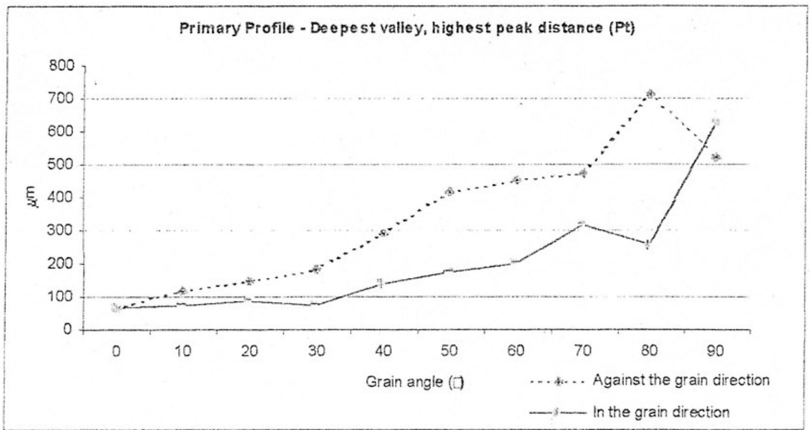


***Figure 11****: Pt of the processed surfaces*

What we have just discussed for visual analysis, is confirmed by both Pa and Pt. In facts we have a progressive worsening of the surface quality going from 0 to 90 and from -0 to -90. At 20° in the grain direction we can see that Pa have an high intensity (large value) while we were expecting a low level; this is due to the different elastic behaviour of early- and late-wood, that leads some bumps to arise on the surface because of the different reaction to the compression carried by the edge during the cut. In facts early-wood is easier to compress and the elastic recovery is higher than in late wood.

3.2 Cutting forces

The measurement of cutting forces during the processing is always difficult, because of the interferences brought by all the vibrations affecting the system. Often the signal is 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 $4^{th}$ 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. In this case the cutting conditions are set as 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 Newton for time-intensity analysis, and an index going from 1 to –1 (1: perfectly correlated - -1: anti-correlated). for autocorrelation.
The first test we have done is to verify the absence of noise while the machine was moving but not processing (see ***Figure 12 – 13***).

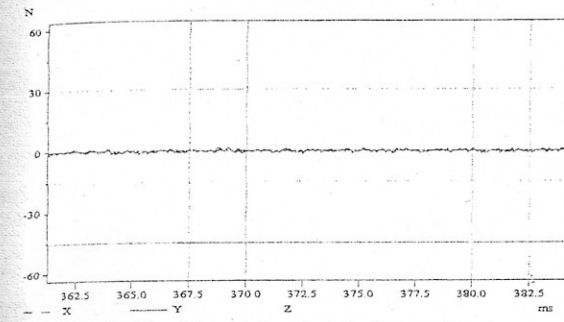


***Figure 12****: Non filtered signal while the machine is moving without processing.*

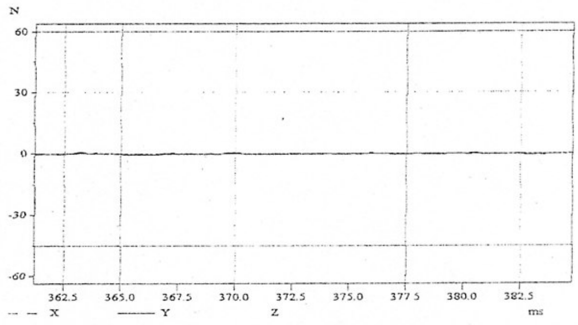


***Figure 13****:Filtered signal while the machine is moving without processing.*

Once verified the absence of significant noise we began the analysis of the signals obtained while processing. The filtered and non filtered signals look like in ***Figure 14 – 15***. As can be easily seen, valleys have a slightly different value in the two cases (filtered and non-filtered), but if the natural 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 analysed this one.

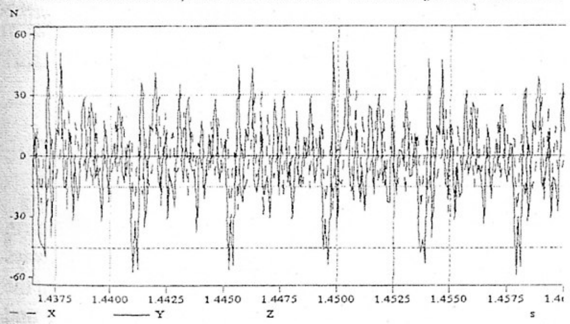


***Figure 14****: Non filtered signal while the machine is moving and processing a specimen with ξ 20°.*

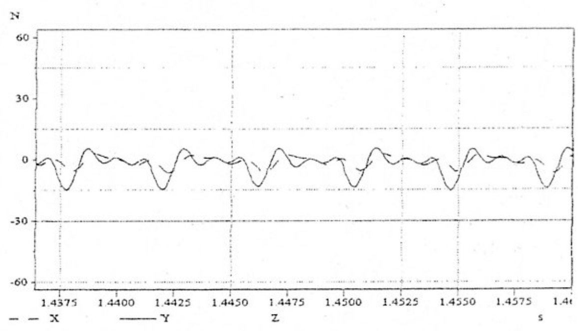


***Figure 15****: Filtered signal while the machine is moving and processing a specimen with ξ 20°.*

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 16 – 17***).

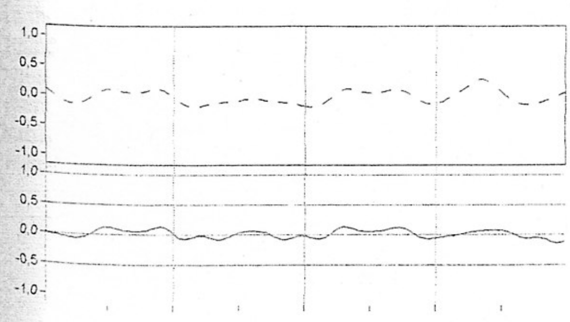


***Figure 16****: Autocorrelation of filtered signal while the machine is moving but not processing.*

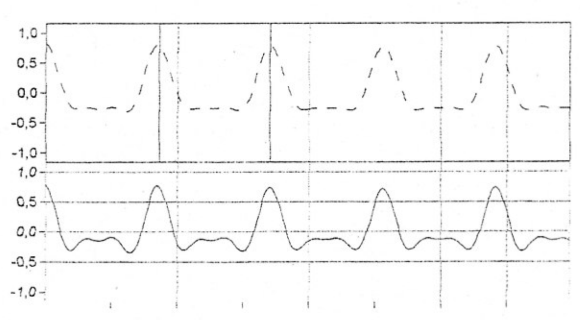


***Figure 17****: Autocorrelation of filtered signal while the machine is processing a specimen with ξ 20°.*

Here follows a deeper analysis of time and autocorrelation functions for a specimens 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 in general the shape is the same (as in ***Figure 18***). As can be seen the axis with the biggest influence is the Y axis (principal force), the one oriented in the same direction of the feeding. From this plot results 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 valley in the graph corresponds to a revolution of the tool, while we have two cutting inserts. 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 remarkable at all. This maybe a limit of the measuring system or, simply depending on the cutting. For the moment we are not able in giving any further information about.

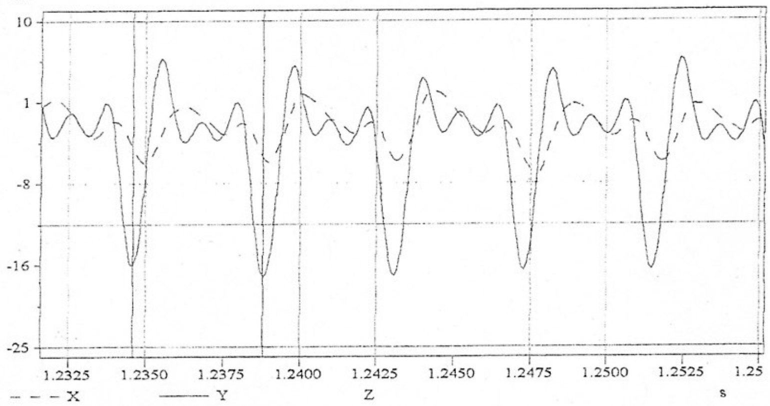


***Figure 18****: Filtered signal while the machine is processing at α 60°.*

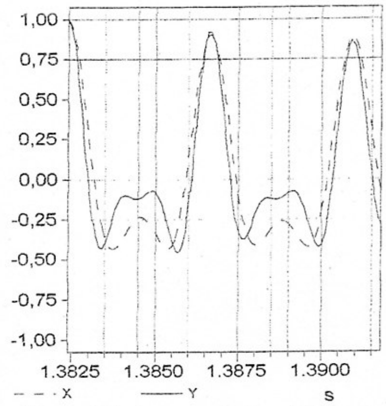


***Figure 19****: Autocorrelation of filtered signal, processing at ξ 60*

As can be seen from ***Figure 19*** the system is periodic and the distance between the first and the second peak is 0,0043 for both the axes, exactly the time necessary for a revolution.
To determine the cutting forces during the process we measured the deepest valley consequent 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***.

| Grain Angle | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| S. D. Along the grain | 0,3 | 0,5 | 0,4 | 0,8 | 0,6 | 0,8 | 0,8 | 1,3 | 0,6 | 0,4 |
| S. D. Against the grain | 0,2 | 0,4 | 0,3 | 1,4 | 0,5 | 0,9 | 0,9 | 0,6 | 0,6 | 0,6 |

***Table 6****: Standard deviation in measuring cutting forces*

**Douglas fir processed along the grain direction** shows a clear behaviour for both the axes. For Y axis the force (in both axes, for comfort we use a positive scale even if considered in our reference system they are negative) is always bigger than for X axis and grows continuously from 0 to 90°. This was expected considering the fiber orientation. In the X axis we found a different behaviour: cutting forces grow up from 0° to 20/30° where they reach the maximum, and after, progressively decrease until 90° This behaviour is theoretically supported by the exam of the interactions between rake face and grain direction.

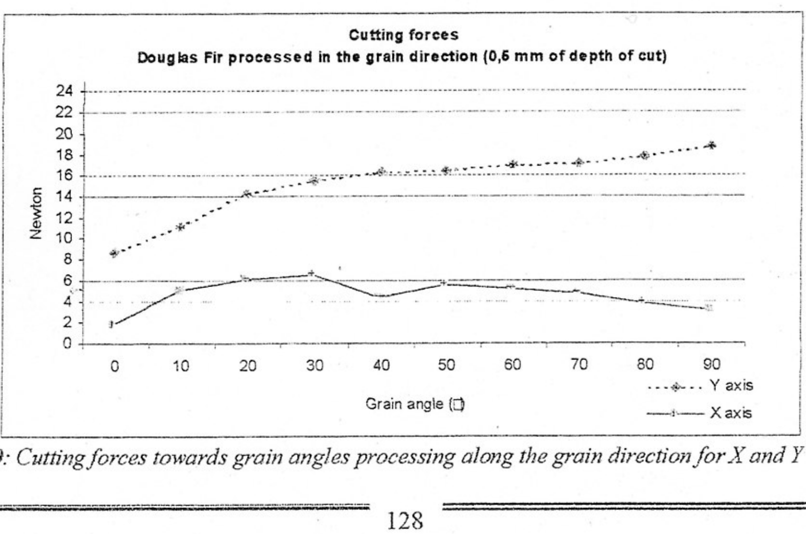


***Figure 20****: Cutting forces towards grain angles processing along the grain direction for X and Y axis*

Looking the evolution of the angle included between the rake face and the grain direction (removal angle - ψ) at the impact and when the blade gets out from the wood (see ***Figure 22***) we evict that from ξ 20 to 33 we have a moment inside the chip where the grain direction and the rake face are perpendicular. This geometrical factor stands to an increase of the cutting forces on the X axis because the cut is more difficult (transverse compression and longitudinal tension). In particular the larger increase should be at about 28-30° because the perpendicularity is in the middle of the chip. This hypothesis is completely confirmed by the cutting forces measurements.

**Douglas Fir processed against the grain** direction shows a clear behaviour for both the axes. For Y axis the force is always larger than in X axis and grows almost continuously from -0 to -90°, with an exception for -70°. This was expected considering the fiber orientation. In the X axis we found a different behaviour, cutting forces grow up from -0° to -10° and decrease slowly reaching the minimum at –70°. This behaviour is theoretically supported by the exam of the interactions between rake face and grain direction

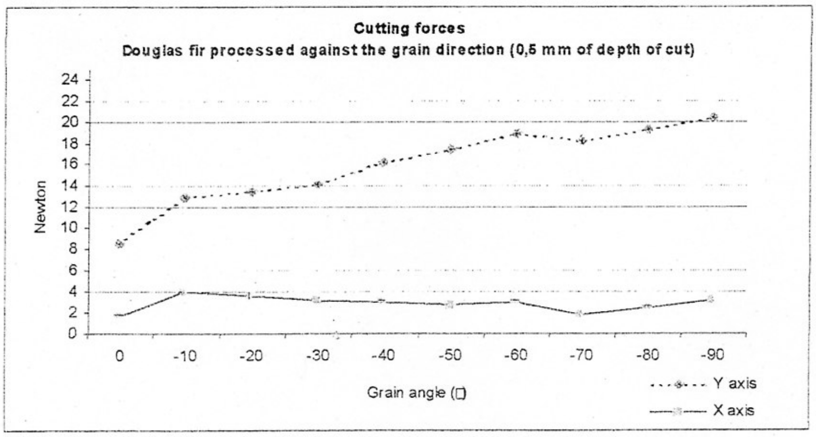


***Figure 21****: Cutting forces toward grain angles processing against the grain direction for X and Y axis*

Looking the evolution of the removal angle (ψ), at the impact and when the blade gets out from the wood (see ***Figure 22***) we evict that from ξ 67 to 80 we have the parallelism between the grain direction and the rake face. This geometrical factor stands to a decrease of the cutting forces on the X axis because the cut is easier (transverse tension). In particular the biggest decrease should be at about 73-75° because the parallelism happens in the middle of the chip. This hypothesis is completely confirmed by the experimental results.

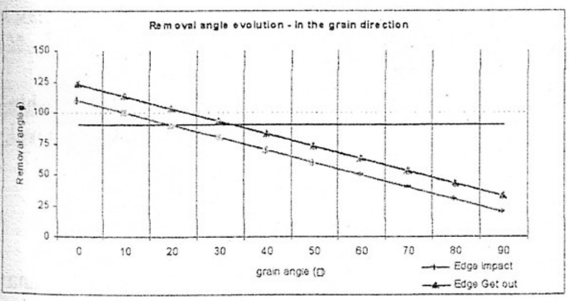


***Figure 22****: evolution of the removal angle (ψ) processing along the grain direction*

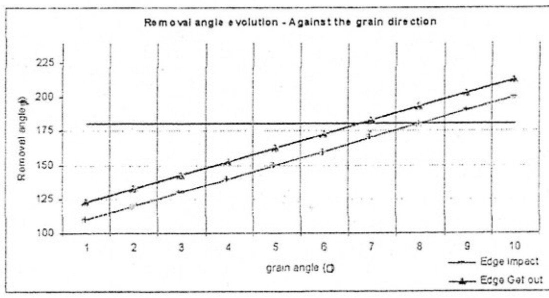


***Figure 23****: evolution of the removal angle (ψ) processing against the grain direction*

In the end we would just compare the cutting forces for both the processing techniques (see ***Figure 24***). For Y axis we found very similar results processing along and against the grain direction. For the X axis we can easily see how the value obtained processing along the grain direction is always larger than the one obtained by processing against the grain direction. In general it is more difficult to process along the grain direction (considering cutting forces and not surface quality), because chip formation occurs for transverse compression, while when cutting against the grain, chip formation occur for transverse tension.

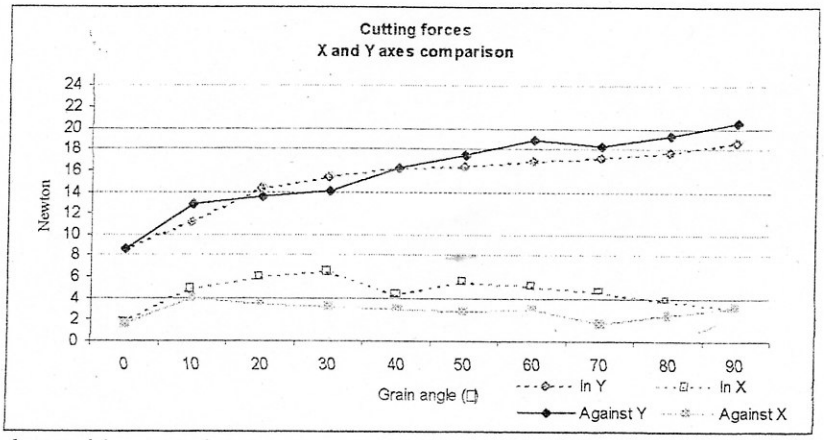


*Figure 24: evolution of the cutting forces, processing along and against the grain direction for both the axes.*

## 4. CONCLUSIONS

To sum-up this experience we can say that Douglas Fir with moisture content of 13,5% ~ has been completely characterised concerning wood processing with up-milling technique at different grain angles. The surfaces have been macroscopically examined, cutting forces have been acquired and analysed, and profiles have been measured and processed. The surface formation process has been briefly discussed and related to measured cutting forces and to processing geometry. The main results of this research are summarised in the following points:

1. Douglas fir processed at different grain angles shows a very different behaviour between early- and late-wood with the same processing settings, and a different behaviour between processing along the grain direction and against the grain direction. From visual analysis the surface quality decreases increasing the grain angle and the surfaces processed along the grain direction are always better than those processed against the grain direction.
2. The above reported statements are supported by profile analysis that show for both calculated parameters "Pa" and "Pt" the same trend macroscopic analysis.
3. Cutting forces analysis shows that only one of the two edges was actually cutting, while the other probably didn't have an important role in the process. Cutting forces evolve with grain angle. Evolution differs for the two axes X and Y and between processing "along" or "against" the grain direction. For Y axis the force always increases when increasing the grain angle. A small exception at –70° has been explained by geometrical reasons. For X axis, when processing along the grain the cutting forces increase from 0 to 30°, and decrease slowly until 90°; while processing against the grain they increase from 0 to –10°, slowly decrease until the minimum is reached at –70°, and again increase until -90°. The cutting forces along the Y axis are always larger than the forces along the X axis. The forces along the X axis are larger when processing along the grain than when processing against the grain.
4. This behaviour along the X axis has been explained by a geometrical hypothesis, i.e. by considering the relationship between rake face and grain direction, and in particular the angle between the rake face and the grain direction (removal angle) to discriminate parallelism or perpendicularity between the two.

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