Wood Processing: a contribute to the interpretation of surface origin according to grain orientation

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Abstract

Surface quality is one of the main factors to be achieved during secondary processing of wood. The technological features influencing the final quality, such as the tool geometry, the chip thickness, the cutting speed, the feeding speed and the friction coefficient have been deeply analysed during the years. The aim of this work is to highlight the reactions of wood to the cutting action, as influenced by its behavior and properties. Specimens of different species with different grain orientation have been processed in a specially developed device for slow orthogonal cutting; both the cutting forces and the behaviour of wood have been recorded and analysed. The mechanisms of surface formation have been analysed in order to give a mechanical interpretation of the surface origin and of the defects appearing at different grain orientations.
*K*eywords: grain orientation, wood machining, chip formation, surface formation

1 Introduction

Many factors in wood processing are involved in the formation of the surfaces and in their final quality. Such factors can be internal or external to the wood. Internal factors concern mainly: the grain orientation, the moisture content, the wood density and the density distribution. External factors concern mainly the machining process parameters such as: the feeding speed, the depth of cut, the tool diameter and geometry, the cutting geometry, the cutting technique (up or down milling). Such factors are influenced by each other and in previous studies have been analysed and studied separately by different Authors. Relevant studies concerning how the cutting forces change when changing internal and external parameters have been described in the pioneering work work of Kivimaa [11]. Kivimaa shown the influence of the main factors listed above on the cutting forces evolution. Many of these factors have been discussed in other fundamental works mainly by Franz [6] and McKenzie [12, 13]. In its work Franz defines the main types of chip (I, II, III) formed when processing parallel to the grain; McKenzie defines the main cutting directions (0-90, 90-0, 90-90) and two main types of rupture patterns (Ia, Ib, IIa, IIb) when processing across the grain. The interactions between the surface and the tool during the cutting have been deeply analysed for various cutting conditions by Woodson and Koch [19], McKenzie and Cowling [14, 15] and Stewart [17]: the

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Authors propose factorial experiments when processing in the main cutting directions in order to improve the knowledge concerning the roles of the different factors (typically moisture content, chip thickness, rake angle) in the cutting process. In their work the above mentioned authors clearly disclose, even if they do not explain completely, the basis to understand the surface origin when processing wood in the three main cutting directions and configure the tools to describe the phenomena acting in the surface formation. Stewart [18] introduce a first important approach to the effect of the cutting direction with respect to grain orientation on the quality of machined surface, on the tool force components and on the cutting friction coefficient. After such basic works not much seems have been done on the subject of processing with different grain orientations. Much work has been done on the optimization of the parameters [4, 5] and on the modeling of the cutting forces [3] often not considering or only to some extents this essential parameter. An analysis of the cutting forces, of the surface roughness and of the acoustic emission when processing with different grain orientations has been done by Cyra and Tanaka [2]. They measured all the mentioned parameters increasing the grain slope by 15° in 15° steps, processing in the 90/0 to the 90/90 plane (with and against the grain), in the 90/0 to the 0/90 plane (with and against the grain) and passing gradually from a tangential cutting condition to a radial cutting condition processing parallel to the grain. However this work being focused on the acoustic emissions in routing they do not report the cutting forces evolution in the 90/0 to the 90/90 plane. Negri and Goli [16] reported a description of the surface quality as a result of the grain orientation when processing with and against the grain in the horizontal plane (from 90/0 to 90/90 cutting conditions) and they also put into evidence the relationship between the surface defects, as described by a visual classification (raised grain, fuzzy grain and torn grain), to be felt as a consequence of the grain orientation. Further investigations about the surface origin and about the cutting forces evolution processing with various grain orientations has been done by Goli et al. [7, 8, 9, 10] and by Costes et al. [1] with two different approaches. In the former case the tests have been carried on in a routing process, in the latter in processing with a turning machine; however, the results in the two cases are very similar. In this paper we focus on the crack propagation and on the variation of the cutting forces during the cutting path as a result of the surface formation mechanics.

2 Material and method

In order to compare and analyse the cutting forces in cutting with different grain orientations we established a low speed cutting test. The equipment used is a universal testing device equipped with a plate sliding along four guides by means of ball bearings, in order to maintain the orthogonality and guarantee the required precision and the repeatability. The sliding plate (upper) carries a tool holder equipped with a WC insert that moving down cuts a wood chip from the specimen. Since the specimen is fixed on a tri-axial dynamometric platform (only two axes has been used in the tests) the cutting forces are accurately measured and recorded during the tool's travel. The apparatus is shown in figure 2. The use of a general purpose testing device implied a cutting speed much lower than in a normal cutting process, which therefore can not be throughly reproduced in these tests; however it allows to accurately observe the process and to measure more precisely the acting forces. Following our previous experiences carried out by measuring cutting forces during dynamic processes [8], the test described here were mainly focused on the observation of the surface formation process in order to better understand the crack propagation while cutting with various grain orientations. Being this a group of preliminary tests the specimens are not uniform and their dimensions were approximately 20 mm in height (length of cut) and of 14 mm in width (width of cut). The depth of cut (chip thickness) was $\sim$ 0,6 mm (increased to $\sim$ 1 mm for a comparative test) and was obtained by the aid of a positioning device after the surface was sharply cut with a precision circular saw. The cutting speed has been fixed in $\sim$ 6 mm/sec. The chip evacuation space was enough for a clear and continuous cut so to prevent any disturbance from other processes, such as friction or compression. The principal force is oriented as the feeding speed and it's positive direction is the same of the feeding speed, the normal force is oriented perpendicular to the surface and it's positive direction goes from the cutting edge inside to the specimen. These two components, measured by the dynamometric platform, have been recorded by the means of a PC acquisition device. Each group of specimens with various grain orientation has been obtained by the same piece of wood, having regular grain; in order to determine precisely the grain orientation the mother piece were previously hewed out by cleavage (see figure 1). The wood piece have have been planed and the specimens have been cut very near to each other, in order to minimize the differences due to the wood variability itself. Such care allow us to consider the grain orientation as the main variable of the experiment.

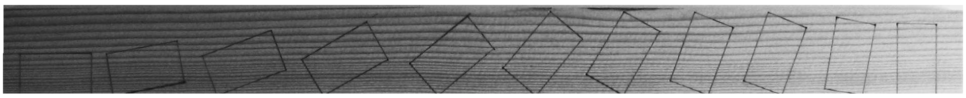


Figure 1: A piece of Douglas fir with the specimens to be cut for the experiment.

The species used in this preliminary test are Douglas fir (*Pseudotsuga menziesii* Franco Var. Menziesii) and Azobé(*Lophira alata* Banks) with a moisture content of $\sim$ 11%. Both Douglas fir and Azobé have been processed along the grain on a tangential face (see figures 3 and 4). Douglas fir has been processed with and against the grain on a radial and on a tangential face in order to compare the differences between processing one or the other (see figures 6 and 7). For the radial face we used two depths of cut in order to show the differences (see figure 9). Before every cut the specimen's surface has been prepared by the means of a circular saw with a very low feeding speed in order to abtain a sharp and smooth surface and consequently an amogeneous chip thickness while cutting.

3 Results and discussion

3.1 The general behaviour of wood when processing with various grain orientations

It is well known that processing wood with different grain orientations leads to a very different final status of the surface. Being defined γ the rake angle, δ the angle between the rake face and the grain and ζ as $\delta - \gamma$ we are processing along the grain if $\zeta = 90\,^{\circ}$; with the grain if $0\,^{\circ} < \zeta < 90\,^{\circ}$; against the grain if $90\,^{\circ} < \zeta < 180\,^{\circ}$, on top if $\zeta = 180\,^{\circ}$. Being defined the cutting as the splitting of the material along the path described by the cutting edge and the deflection of the split material, in most of those cases the material it is not cut. In facts the material splits but not along the cutting path. This is the base for the formation of defects in wood machining. The first consequence is that the models considered as working in normal cutting conditions can not be applied in most of the cases of defect origin because the material is not cut [9]. Moreover, even if the analysis of the surface formation as resulting by processing with different grain orientation can already give some

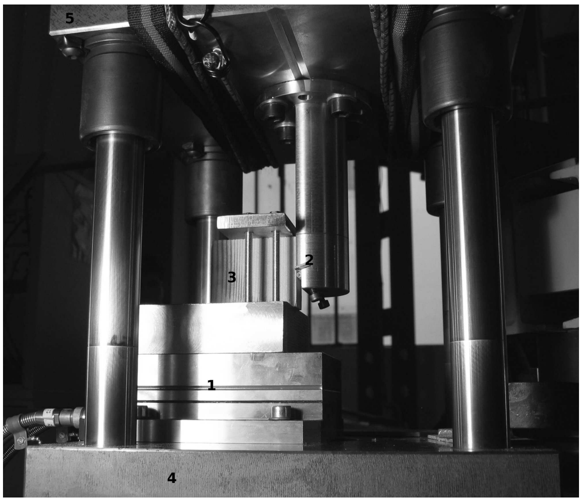


Figure 2: The testing apparatus: 1) the dynamometric platform 2) the tool holder and the tool 3) the specimen 4) the lower plate 5) the upper plate.

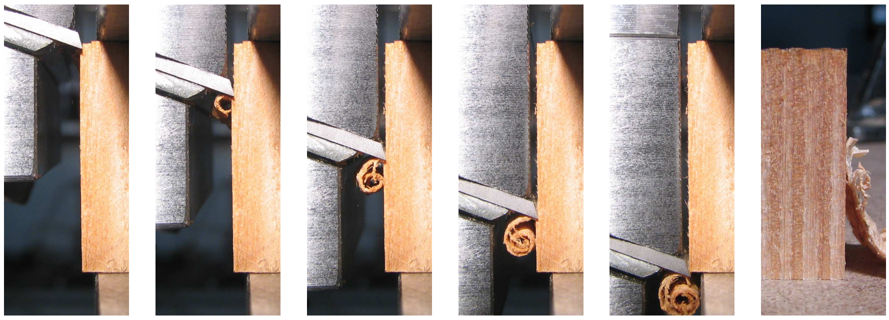
general laws [10], the reaction to the splitting should be studied considering a wide range of factors (moisture content, specific gravity).

3.2 The chip formation

In the secondary processing of wood chips are the waste of the process itself. Chips have a theoretical shape (cycloid shape when processing with turning tool) that only in rare cases result as real while cutting. Processing along the grain or with the grain with narrow angles usually results with the theoretical chip. All the other cutting conditions usually result in a destruction of the chip that often is pulverized. The cutting process can be imagined as a splitting only in a few cases, when cutting in optimal cutting conditions. The changing of the grain orientation results in changes in the normal and principal force according to the characteristics of the material. The reaction of the wood to the splitting at the beginning of the cut can be by transverse tension (when processing against the grain) or by transverse compression (when processing with the grain), and the evolutions of the surface cutting mechanics depends mainly on this first important contact.

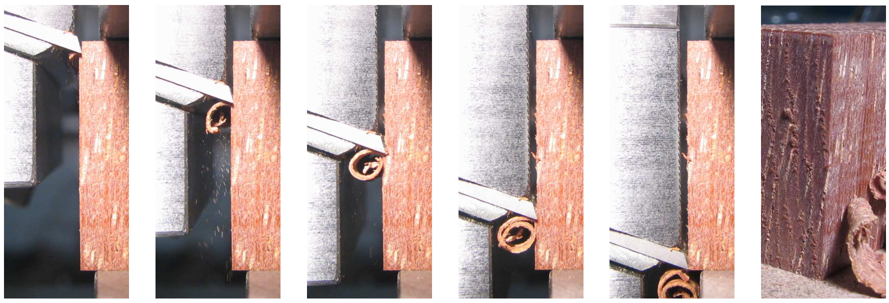
3.3 Chip formation processing tangential specimens along the grain

As can be seen for Douglas fir and Azobé in the sequences of cut (figures 3, 4) and in the cutting forces diagram (figure 5) the chip formation processing along the grain is a semi-continuous process. In Douglas fir it is very clear how the principal force acts in a semi-continuous way, while the normal force can be considered as acting continuously. The behaviour of the principal force is because of the fracture propagation (chips type I), that after started leads to a decrease of the principal force that increase once starting again the cut. The normal force have a more continuous behaviour because being mainly due to the friction force exerted by the back of the tool it does not change significantly. Processing Azobé we can observe something very similar to Douglas fir even if the principal force is less discontinuous. This is because the propagation of the fracture is easier for Douglas fir than for Azobé. The surface quality as can be seen in figures 3(f) and 4(f) can be considered good.



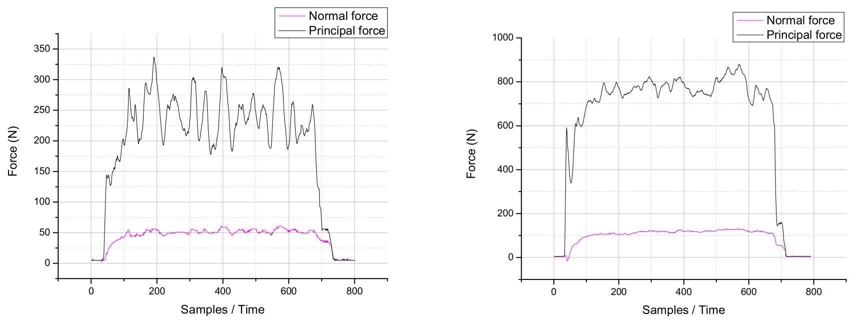
(a) (b) (c) (d) (e) (f)

Figure 3: Sequence processing a tangential specimen of Douglas fir along the grain with a depth of cut of ∼ 0,6 mm.



(a) (b) (c) (d) (e) (f)

Figure 4: Sequence processing a tangential specimen of Azobé along the grain with a depth of cut of ∼ 0,6 mm.

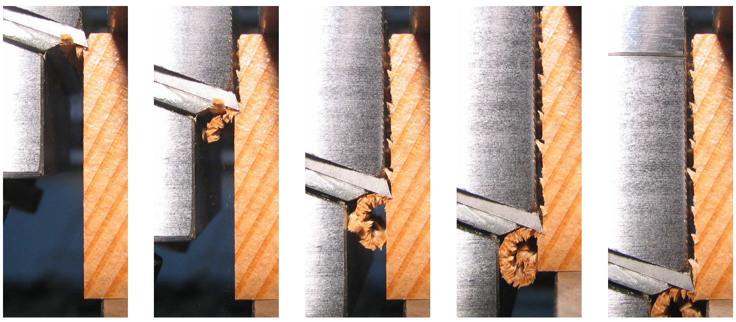


(a) (b)

Figure 5: Cutting forces processing tangential specimens of Douglas fir (a) and Azobé (b) along the grain.

3.4 Chip formation processing radial specimens with and against the grain

Processing radial specimens the interaction between early and late wood becomes more important especially processing against the grain. Processing with the grain results in a semi-continuous process with some peaks of force cutting the late wood. As can be seen in figures 6 and 8(a) at the beginning of the cut the blade cuts the early wood and the first group of fibers splits along the grain leading to a decrease of the principal force. After this first contact the principal force increase and decrease cutting late and early wood. The normal force seem not to be affected by this process. The normal force has a semi-continuous behaviour possibly due to the compression of groups of fibers before being split. The cutting forces magnitude is similar to that resulting by processing along the grain (see figure 5) but the processes acting are very different. Processing against the grain the cutting forces increase very much (1400N processing against the grain vs. 300N processing with the grain for the principal force and 600N vs. 50N for the normal force), this is connected with the thickness of the chip. In facts even if the theoretic thickness is the same as with the grain the fibers being pushed down and being turned present a real chip thickness much higher than in theory. It becomes essential to distinguish between *"theoretic chip thickness"* and *"real chip thickness"*. Processing against the grain in the last part of the diagram we can observe a rise of one or both the cutting forces. This is because in our testing device the last part of the sample that is torn away for transverse tension remains compressed between the blade and the specimen holder resulting in a unexpected rise of the forces. This fact it is not connected with the cut as can be seen in figure 7(e).



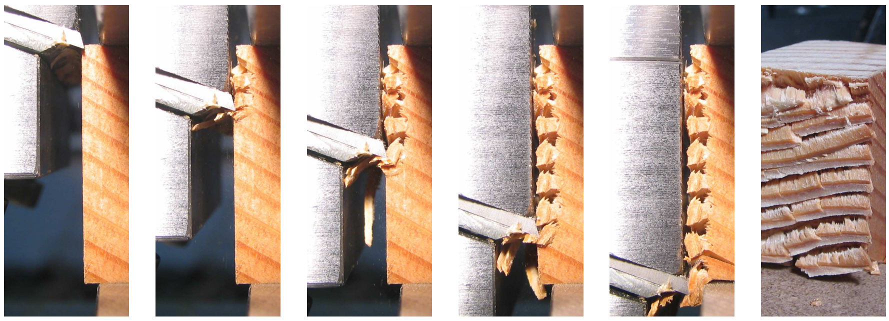
(a) (b) (c) (d) (e)

Figure 6: Sequence processing a radial specimen of Douglas fir 30 ° with the grain with a depth of cut of ∼ 0,6 mm.

Processing with a higher theoretic chip thickness (∼ 1 mm) both the principal and normal forces rise (1400N vs. 2800N for the principal force and 600N vs. 1200N for the normal force as can be seen in figures 8 and 10). As in figure 9 the surface is completely destroyed and it is not easy to define a chip and a chip type. In this case it is manifest how early and late wood cooperate in the destruction of the surface.

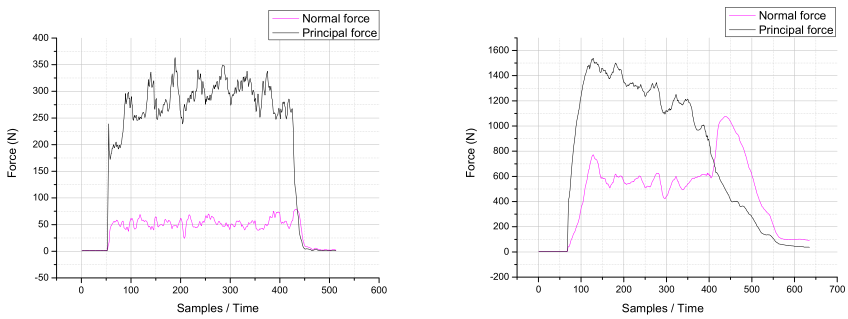
3.5 Chip formation processing with and against the grain tangential specimens.

In processing tangential specimens the cut can be considered as more continuous for both processing with and processing against the grain. The cutting forces processing



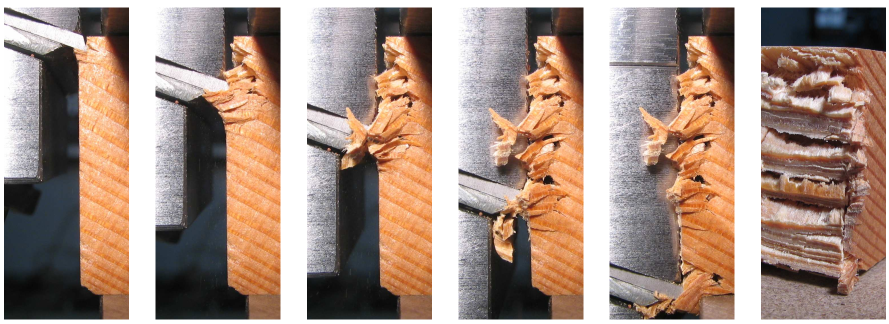
(a) (b) (c) (d) (e) (f)

Figure 7: Sequence processing a radial specimen of Douglas fir 45 ° against the grain with a depth of cut of ∼ 0,6 mm.



(a) (b)

Figure 8: Cutting forces processing radial specimens of Douglas fir 30 ° with the grain (a) and 45 ° against the grain (b).



(a) (b) (c) (d) (e) (f)

Figure 9: Sequence processing a radial specimen of Douglas fir 45 ° against the grain with a depth of cut of ∼ 1 mm.

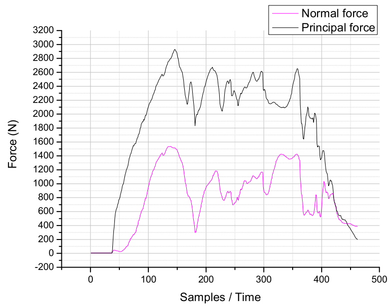
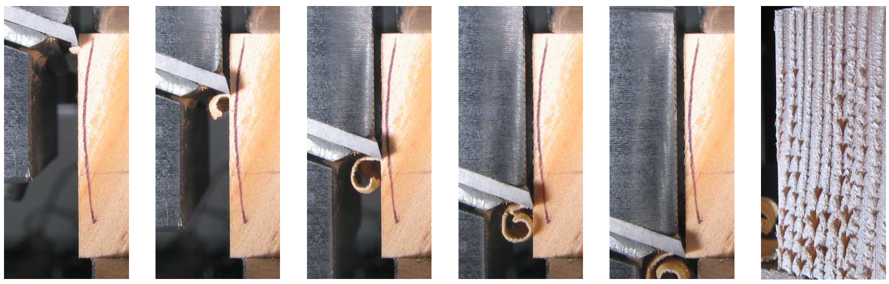


Figure 10: Cutting forces processing a radial specimen of Douglas fir -45 ° against the grain with a depth of cut of ∼ 1 mm.

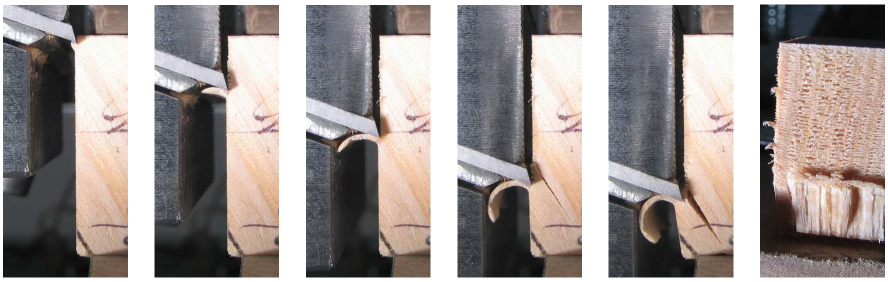
with the grain tangential specimens are in line with those measured processing with the grain radial specimens with a similar chip thickness (see figures 6 and 11 for the cutting sequence and figures 8(a) and 13(a) for the cutting forces). In the final surface is clear the different reaction processing early and late wood (see figure 11(f)). Fuzzy grain appears only in the early wood, while late wood is sharply cut. As can be seen by the cutting forces, even because the early and late wood do not interact, the process is very continuous, especially for the normal force. The irregularities of the principal force can be achieved to the formation of packets of fibers that when cut leads to a decrease of the cutting forces. Processing against the grain being the grain slope different from the radial specimen (30 ° vs. 45 ° - figures 7 and 8(b) vs. 12 and 13(b)) we can not make a comparison. Processing tangential specimens the turning of the fibers and consequently the "real chip thickness" is lower than for radial specimens, because of the collapse of the early wood the cellular elements tilt more. In figure 12(d) can be observed the propagation of a fracture that does not leads to a brake of the specimen. The specimen finally brakes in a different point but always in the grain direction as can be seen in figure 12(e).



(a) (b) (c) (d) (e) (f)

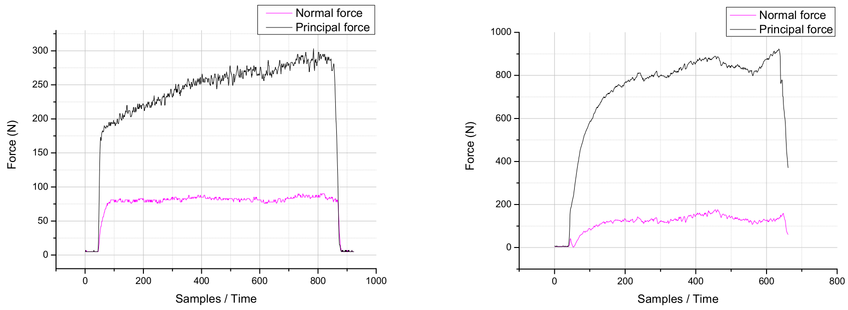
Figure 11: Sequence processing a tangential specimen of Douglas fir 30 ° with the grain with a depth of cut of ∼ 0,6 mm.

In many cases have been observed compression phenomena on the surface before the splitting of the material that leads to cyclic processes on the surfaces. Processing 70 ° against the grain (seen figure 14) what happens is the clear formation if packets of fibers (layers) that are tilted and compressed before being cut. This cyclic process can be seen on the final surface and the cutting forces are well connected with the process itself. The principal force increase progressively while the fibers are



(a) (b) (c) (d) (e) (f)

Figure 12: Sequence processing a tangential specimen of Douglas fir 30 $^\circ$ against the gain with a depth of cut of $\sim$ 0,6 mm.



(a) (b)

Figure 13: Cutting forces processing radial specimens of Douglas fir 30 $^\circ$ with the grain and 30 $^\circ$ against the grain with a depth of cut of $\sim$ 0,6 mm.

compressed. Once the force is enough to begin the tilting of the layer, the cellular elements begin to tilt and the force remains constant until the blade begin the cut and the principal force slope down. The normal force contrarily to the principal force reach its maximum during the tilting of the fibers and the last compression stage before the cut begins.

4 Conclusions

In conclusion the aim of this work is to contribute to the understanding of the surface formation mechanics. We shown how a great part of the mechanisms that contribute to the surface formation are still unclear. According with this analysis we shown how the chip types described in literature represent only a little part of the chips really forming during the cut with different grain orientations. To go forward in the surface formation mechanisms it is essential to understand and describe these processes, and describe the cutting forces evolution in the time and give an interpretation and a modeling of the cyclic processes taking place on the surface. The study of the cutting forces as a mean on the length of cut can not help in the understanding of the surface formation mechanisms. To this understanding

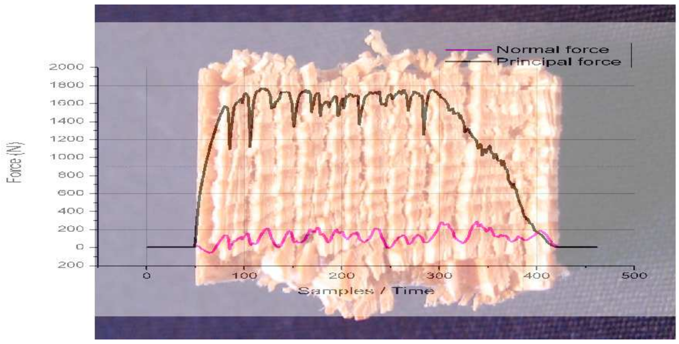


Figure 14: Surface and cutting forces processing a tangential specimen of Douglas fir 70 $^\circ$ against the grain with a depth of cut of $\sim$ 0,6 mm.

can still contribute low speed systems for orthogonal cutting, that even presenting serious limits, seem to be very effective in the understanding of the processes acting and in the explanation of the periodicity of the system. The weakness and tenacity of wood in the transverse plane seem to be the factors determining the attitude of wood in order to be processed. Further experiments in this field are already planned and they will help us to define the parameters describing the attitude of the wood in order to be processed.

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