# Chip formation in wood cutting with different grain orientations using high and low cutting speeds

Goli G.[1], Wyeth D.[2], Atkins A.G.[2], Jeronimidis G.[2], Fioravanti M. [1], Del Taglia A. [3]

[1] University of Florence, Dip. Scienze e Tecnologie Ambientali Forestali, Florence (IT), giacomo.goli@poste.it, marco.fioravanti@unifi.it.

[2] University of Reading, School of Construction Management and Engineering, Reading (UK), d.j.wyeth@reading.ac.uk, a.g.atkins@reading.ac.uk, g.jeronimidis@reading.ac.uk.

[3] University of Florence, Dip. Meccanica e Tecnologie Industriali, Firenze (IT), deltaglia@ing.unifi.it.

## Abstract

The behaviour of wood when cutting with different grain orientations has been investigated at high and low cutting speeds using an orthogonal cutting technique. In both cases special devices have been manufactured. A materials testing machine was adapted for replicating low speed cutting and a Hopkinson bar system was modified to replicate the high speed cutting. The images of the cutting were acquired by sequential photographs when cutting with low speed and with a high speed camera when cutting at high speed. The process of chip formation is compared, analysed and discussed. The stiffening effect of the speed is highlighted as is the effect of dynamics in the formation and expulsion of the chip.

**Keywords**: Wood machining, Chip formation, Grain orientation, Cutting speed influence, Surface quality, Orthogonal cutting

## 1 INTRODUCTION

Wood cutting is very difficult to model and poorly understood because of the orthotropic anisotropy of the material itself and because of the non homogeneity of its structure. When modelling wood cutting many different parameters should be taken into consideration: moisture content, temperature, species, grain orientation, ring orientation, ring width, percentage of early and latewood, density of early and latewood, presence of anomalies. The main problem in modelling wood cutting is that the mechanical properties change when changing the anatomical direction. In the field of wood cutting with different grain orientations have already been performed during the years by several authors using different techniques such as turning tools [4,2], orthogonal cutting [5,7,8,3] and by turning [1]. And the work already performed on composite materials [6] such as carbon fibre reinforced plastics can be successfully transferred to wood. In wood machining when producing complex pieces the grain orientation is subjected to change and this is a fundamental factor in order to understand the wood cutting process. When cutting wood, in fact the same forces applied in different directions result in different behaviours of the material and a specific approach is required. To give a contribution to the understanding of chip formation when processing at different cutting speeds and grain orientations some tests have been performed.

## 2 MATERIAL

The tests were performed on Douglas Fir (*Pseudotsuga Menziesii* Franco Var. Menziesii). The samples used were of constant dimensions and equilibrated at nearly the same moisture content that for Douglas Fir was about 12%.. The specimens were cut from straight grain tangential boards and in close proximity in order to minimise the effects of the wood variability. The boards chosen were without defects and were conditioned to a homogeneous moisture content. The specimens were 14 mm width, 20 mm long and a minimum 35 mm deep in order to offer a base large enough to be firmly held in the device. In some cases, in order to obtain a better cut, a specimen’s length (cutting length) was reduced to 10 mm.

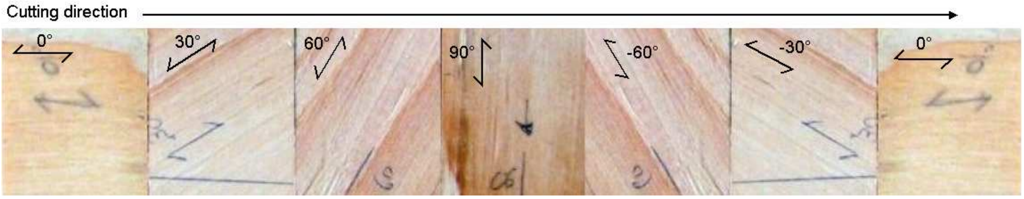
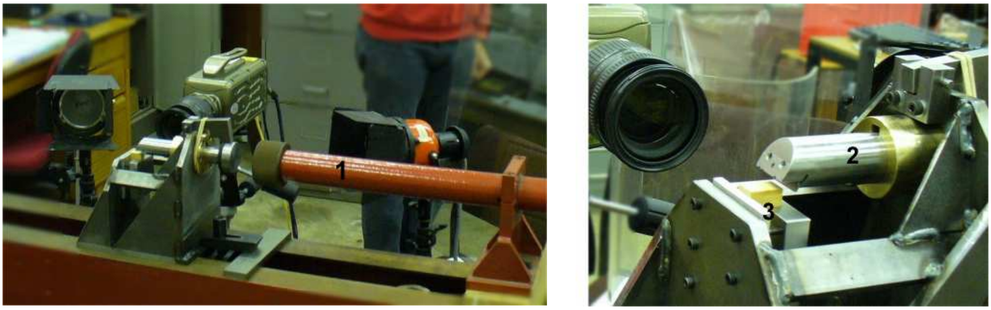


Figure 1. A series of samples of Douglas Fir with different grain orientations.

## 3 METHOD

During the tests for both high and low cutting speeds the grain orientations were varied progressively in 30° increments. The cutting technique in both cases was “free orthogonal cutting”. The blade was a commercial insert for wood made of sintered tungsten carbide. The blade geometry was as follows: γ (rake) 20°, β (wedge) 55°, α (clearance) 15°. The orientation of the specimens was tangential. The specimens were processed: along (0°), across (90°), with (30° , 60°) and against (-30, -60) the grain. The cutting speeds were set to 5x10-3 ms$^{-1}$ for the low speed cutting condition and to ~ 8 ms$^{-1}$ for the high speed cutting condition. For the low speed cutting tests a conventional material testing device was adapted by mounting a stiff blade holder to the hydraulic ram, which was guided on 4 steel columns by linear roller bearings. For low cutting speed the nominal depth of cut was varied between 0,1, 0,2, 0,4 and 0,6 mm. This method is explained in more depth in [3]. The specimens were firmly fixed in position on the base by a compression plate. A tri-axial dynamometric platform was used to acquire the cutting forces: they have not been used for the investigation reported in this paper. The cutting was photographed in sequence using a digital camera at a rate of 2 frames per second. For the high speed cutting a Hopkinson bar system was adapted to incorporate a specially designed cutting rig (see Figure 2). The rig consisted of a base which housed a brass guide ring and a sliding bar to which a cutting blade was fixed (Figure 2b -2). The motion was transferred to the sliding bar by the impact of the Hopkinson input bar, propelled at high velocity by a pressure system (Figure 2a - 1). The specimen was held in position by a compression plate (Figure 2b - 3).The cutting was filmed using a Phantom 7 high speed camera (13 kfps).



a b

Figure 2. The adapted Hopkinson's Bars system used in the high speed tests.

In both cases the desired depth of cut was obtained by pushing the specimen against 0,1; 0,2; 0,4 and 0,6mm removable dead stops. The use of a dead stop instead of an automatic advancing system is required owing to the fact that after every cut the reference surface must be prepared again (by cutting at very low cutting speed with a precision saw or by a router) because in many cases (especially processing with or against the grain) the surface is completely destroyed.

## 4 RESULTS AND DISCUSSION

Both cutting devices have been shown to work adequately and safely. The low cutting speed rig was very stiff so that dynamic problems were absent thus giving a very good precision in the depth of cut. In the high speed system the need for a minimal clearance between the brass guide and the sliding shaft allowed some movement in the vertical plane (especially after the impact of the input bar) which resulted in a varying depth of cut during the cutting length. By shortening the sample and lengthening the brass guide ring the vertical movement was reduced to about 0,05 mm. The influence of the grain orientation at low cutting speed has already been discussed in [3]. In the following section we shall discuss the influence of the cutting speed when processing along the grain, its influence on the surface finish and its influence on chip formation with different grain orientations.

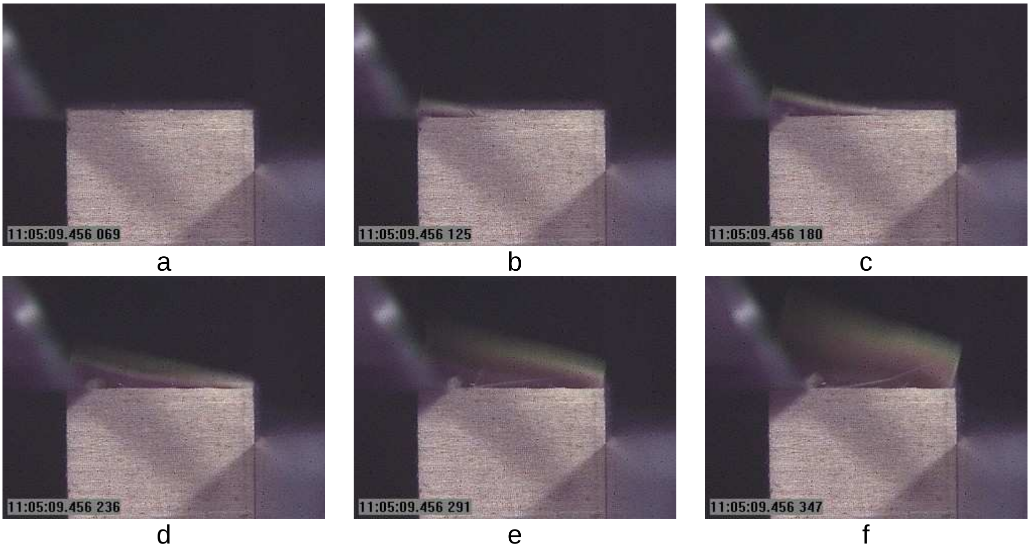
### 4.1 Influence of the cutting speed processing along the grain with different depths of cut

In order to understand the role of the cutting speed, tests with different depths of cut have been performed processing along the grain (0°) . In fact, just changing the depth of cut in wood cutting results in different cutting mechanics. At low cutting speed the cutting mechanics can go through the formation of a shear plane and a steady state cutting condition for the thinnest chips (0,2 mm - see Figure 3a) to the formation of a shear plane or of short fractures and discontinuous cutting for the medium sized chips (0,4mm - see Figure 3b) until the propagation of a fracture that goes through the entire specimen for the thickest chips (0,6 mm - see Figure 3c). This evolution of the cutting process has been observed by varying the depth of cut. By keeping the depth of cut constant and changing the cutting speed, the chip formation mechanics was also shown to significantly change.

a b c

Figure 3. Douglas Fir processed at low speed with 0,2-0,4-0,6 mm of d.o.c..

The dynamic stiffening effect of the speed allowed fractures to easily propagate in the material. That is the same chip formation sequence as found with low speed cutting conditions was obtained (shear plane-->discontinuous cutting with short fractures-->long fractures propagating inside the sample). However, the transition thickness between one process and the other was found to be much lower than observed in low speed cutting. Figure 3b shows the cutting of a 0,4 mm thick chip at low cutting speed. The formation of a shear plane can be observed and this produced a steady state cutting condition. Figure 4 shows the cutting of a 0.4 mm thick chip at a high cutting speed. It is clear that in this case fracture is the main chip formation process, and the fracture was seen to propagate very rapidly to the end of the specimen. The chip was completely detached in 150 µs. In this time the blade moved 1,2 mm, whilst the fracture had travelled the 10 mm length of the sample with a propagation speed of 66,6 ms$^{-1}$. During low speed cutting a behaviour similar to this was observed with a 0,6 mm of depth of cut. In order to obtain a shear plane chip formation in Douglas Fir, whilst processing at high speed, the required chip thickness was found to be less than 0,1 mm.



a b c

d e f

Figure 4. Douglas Fir processed at high speed with 0,4 mm of d.o.c. and a cutting length of 10 mm

In some cases, whether processing at high or low cutting speeds, the fracture propagated in front of the tool leaving only a minimal layer of material that was cut with the formation of a shear plane (see figure 5). In this specific case the formation of the fracture depends also by the presence of a transition zone between early and latewood in the cutting path. The latewood, being denser than early wood, fractured easily. This is another aspect to be taken into account when trying to understand or model the cutting of wood.

Figure 5. Dougls Fir processed at high speed with 0,2 mm of d.o.c.

## 4.2 Influence of the cutting speed on the final surface

One of the main differences between processing at low or high cutting speeds can be observed in the surface finish. High cutting speeds result in a much higher surface finish quality especially for early wood. The improvement of the quality is very pronounced cutting along the grain with different grain orientation it is not so manifest. Figure 6 illustrates a surface obtained processing along the grain with high (Figure 6a) and low (Figure 6b) cutting speeds.

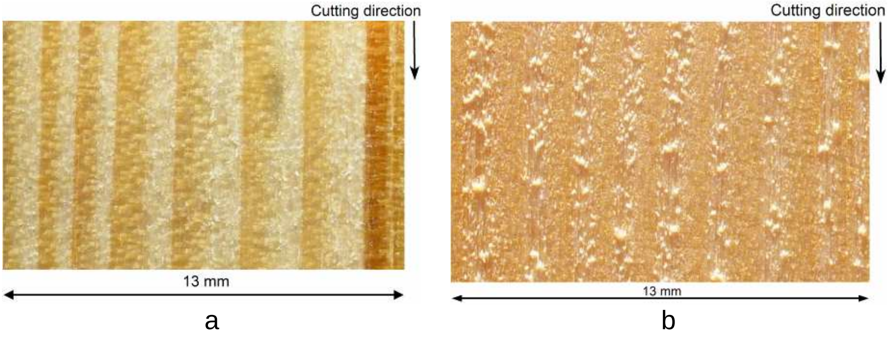


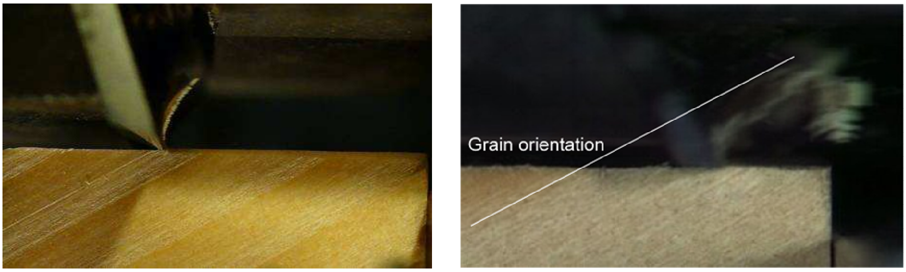
Figure 6. Douglas fir processed along the grain at high (a) and low cutting speed (b) with 0,2 mm of d.o.c.

In this case the stiffening effect of the material as a result of the cutting speed could be clearly seen. The early wood, being less dense and rigid than the latewood, was pushed and compressed by the blade when processed at low speed, instead of being cut by the blade. The cutting of such material, whose density can be as low as 200-250 kg/m$^3$ (the latewood can be 900-1000 g/cm$^3$) is very difficult at low cutting speeds. Increasing of the cutting speed enabled the material to be cut instead of being deformed by the blade, resulting in a much higher final surface quality. For the latewood a reasonable quality was obtained when processed at both low and high cutting speeds.

## 4.3 Influence of the cutting speed on the chip formation with different grain orientations

This section investigates the cutting process at each considered grain orientation at a depth of cut of 0,2 mm.

**4.3.1** Processing with **30°** grain angle (g.a.) (see figure 7). When processing “with the grain”, fibers were transversally cut and pushed to slide along the grain for longitudinal shear. This behaviour at low cutting speeds led to the formation of a segmented chip. The dynamic effect shown in figure 7b led to the formation of a fragmented chip, where single segments that at low cutting speed remained joined together are projected far away from the rake face. At high speed, the single segments slide along the rake face at first and then they are projected perpendicularly to it, because in this case the grain is almost perpendicular to the rake face.



a b

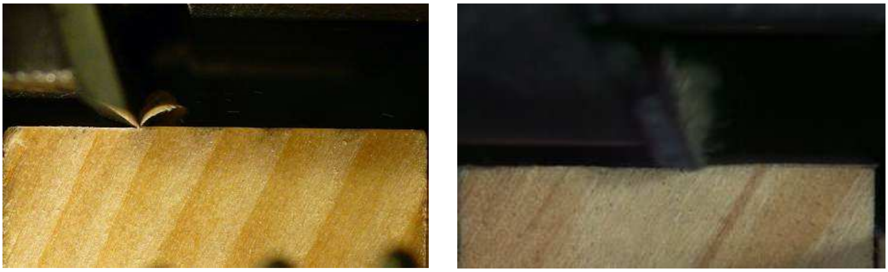
Figure 7. Douglas Fir processed at 30° of grain angle with low (a) and high (b) speed with 0,2 mm d.o.c.

**4.3.2** Cutting with **-30°** of g.a. (Figure 8) resulted in a short compressed chip and fractures were observed to follow the grain. Low cutting speeds tended to rotate the grain, increasing the chip thickness, whilst at the higher cutting speed the dynamic stiffness prevented the grain from rotating. With both low and high speed cutting, fractures propagate into the specimens towards the end of the cut resulting in the last part of the sample being completely detached. One fully-opened fracture and a partially-opened one can be observed in Figure 8b. It shows clearly how a surface defect can occur after the cutting blade has passed. In Figure 8b shows the compression of the chip that is still attached to the blade after having cut several millimetres. The last part of the specimen was completely removed by the moving blade after the propagation of the fracture.

a b

Figure 8. Douglas Fir processed at -30° of grain angle with low (a) and high (b) speed with 0,2 mm d.o.c.

**4.3.3** Processing with **60°** of g.a. (Figure 9) with low cutting speed produced the same phenomenon as observed with the 30° of g.a. Transverse compression was the main stress applied instead of longitudinal shear as found in the previous case. Cutting mechanics progressively converge at 90° both when processing with and against the grain. Transverse compression was the main stress during low speed cutting, and when the wood is cut chips remain together because of adhesion subsequent to the compression. At high speed, because of the higher energy with the impact of the rake face, a very high fragmentation was obtained and the fragments were projected far from the rake face. In contrast the 30° samples produced segments that were projected in the same orientation as the grain and perpendicularly to the rake face. In this case the chip was highly fragmented and fine particles traversed the rake face. Figure 9b illustrates the role of the grain direction in the formation of unhealthy dust.



a b

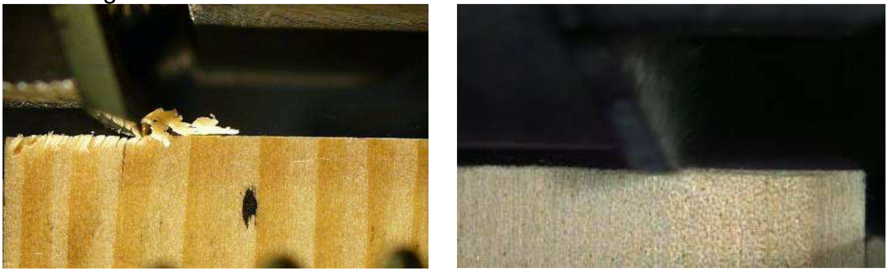
Figure 9. Douglas Fir processed at 60° of grain angle at low (a) and high (b) speed, 0,2 with 0,2 mm d.o.c.

**4.3.4** With **-60°** of g.a. (Figure 10) processing at low cutting speed, a high compression of the chip could still be observed (Figure 10a). This transverse compression is still possible with high speed cutting (Figure 10b) but as for 60° the resultant chips fragmented, pulverised and the parts were propelled far from the blade. At 60°, -60° and 90° as previously explained, during the cutting process the wood is subject to a high transverse compression. When processing at high cutting speed the resultant chip was highly fragmented and the impact with the rake face resulted in the projection of the fragments.

a b

Figure 10. Douglas Fir processed at -60° of grain angle at low (a) and high (b) speed, with 0,2 mm d.o.c.

**4.3.5**. Processing with and against the grain the chip formation mechanics progressively converge at a g.a. of **90°**. Cutting at low speed the chip was not completely destroyed but was extensively compressed. As with 60° and -60° of g.a., processing at high speed, the chip was completely destroyed. The particles of chip traversed along the rake face.



a b

Figure 11. Douglas Fir processed at 90° of grain angle at low (a) and high (b) speed, with 0,2 mm d.o.c.

## 5 CONCLUSIONS

In conclusion the basic mechanics of the orthogonal cutting process when cutting with low and high cutting speeds have been analysed and discussed. Processing along the grain at both cutting velocities gives chip thickening that results in the formation of a fracture during cutting instead of a shear plane. This is due to the stiffening effect caused by the higher cutting speed. With low cutting speeds the chip thickness threshold to pass from cutting by the formation of a shear plane to fracture was found at around 0,4 mm, whilst processing at high speed the threshold was found between 0,1 and 0,2 mm. In high speed cutting along the grain the fracture propagation speed was measured at approximately 66 ms$^{-1}$. Cutting along the grain at both high and low speeds produced two cutting mechanisms were observed acting simultaneously during the chip formation. In the first contact time between blade and wood a large fracture propagation was observed. As the fracture was not perfectly on the cutting line some material was subsequently removed during the tool passage, and as this remaining material was a thin layer, a shear plane chip formation was obtained. Another fundamental effect observed is on the final surface quality, and in particular on the early wood. The dynamic stiffening effect was found to make a significant difference when cutting early wood. At low speed the early wood behaved like a soft foam and resulted in extensive compression and tearing. The higher speed resulted in a better final quality of the surface, at least whilst processing along the grain. Processing at the other grain orientations did not result in such a big improvement. Finally the dynamic effect on the chip formation at different grain orientations, processing with and against the grain was studied. For both the cutting settings similar behaviours are observed in terms of interactions between fibre and grain. Finally processing with low cutting speed resulted in a very compressed chip, while processing with high cutting speed resulted in a much more fragmented chip. The chip parts are propelled away after the impact on the tool surface and this plays a fundamental role in increasing the fragmentation of the chip and in the formation, and spreading, of micro powders that are a health risk.

## ACKNOWLEDGEMENTS

We would acknowledge the European Science Foundation, the COST office and the COST E35 action for the financing of two Short Term Scientific Mission that make possible this work.

## REFERENCES

[1] Costes, J.,P., Lim Ko, P., Decés-Petit, C., Altintas, Y., 2002. Orthogonal cutting mechanics of maple: modelling a solid wood-cutting process, *J. of Wood Sci.* 50-1: 28-34

[2] Goli, G., Marchal, R., Uzielli, L., Negri, M., 2003. Measuring cutting forces in routing wood at various grain angles. Study and comparison between up and down-milling techniques, processing Douglas fir and oak, *Proceedings of the 16th International Wood Machining Seminar*, 127-137.

[3] Goli, G, Fioravanti, M, Sodini, N, Jiangang, Z, Uzielli, L, 2005. Wood Processing: a contribute to the interpretation of surface origin according to grain orientation, *Proceedings of the 17th International Wood Machining Seminar* 44-54.

[4] Kivimaa, E., 1950. Cutting force in woodworking. *State institute for Technical Research, VTT Publication No. 18*

[5] McKenzie, W., M., 1961. Fundamental aspects of the wood cutting process, *PhD. Thesis University Michigan Ann Arbor*.

[6] Lopresto, V., Santo, L., Caprino, G., De Iorio, I., 1999. Effect of fibre orientation on cutting forces and cut quality in machining unidirectional carbon fibre reinforced plastics, *Proceedings of the IV Conv. AITEM, pp.451-454*

[7] Stewart, H. A., 1969. 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(3): 43-46.*

[8] Stewart, H. A., 1971 Chip formation when orthogonally cutting wood against the grain. *Wood Sci. Tecnol. 3(4): 193-203.*