Machining of Wood using a Rip Tooth: Effects of Work-piece Variations on Cutting Mechanics

Naylor, Andrew.[1*]   Hackney, Philip.[1]   Clahr, Emil.[2]

[1]School of Computing, Engineering and Information Sciences, Ellison Building, Northumbria University, Newcastle upon Tyne, NE1 8ST, United Kingdom
[2]Research and Development Centre for Wood Working, SNA Europe, Box 1103 82113 Bollnäs, Sweden

ABSTRACT

Genetics and environmental conditions during the growth of wood are known to affect the intrinsic characteristics influencing cutting mechanics. To evaluate this, a full factorial experiment has been performed investigating the effects of three significant factors involved in wood machining; wood species, moisture content and grain direction. A variety of woods were evaluated (five softwood and three hardwood species) at four moisture levels. As all woods are heterogeneous, anisotropic materials, machining was performed parallel and perpendicular to the grain direction. A three axis CNC router was used to drive a tool resembling a rip tooth, at low velocity, through each of the sixty-four wooden work-piece variations at three different depths of cut. To collect quantitative data, a piezoelectric dynamometer was used with a data acquisition system to measure and record the cutting and thrust force components acting on the tool. Chip formation and work-piece deformation was observed using images taken from an optical microscope. In this paper the results from the rip tooth experiment are compared to published results [1-7] in for planing operations from fundamental literature.

INTRODUCTION

Research performed into optimum wood machining conditions [1, 2] suggests that there are three significant types of factor that affect the cutting mechanics:

1. Factors attributed to the machining process
2. The species of the wood
3. The moisture content of the wood

Wood has three orthogonal planes of symmetry; axial, radial and tangential. Corresponding to these planes of symmetry are several different cutting directions by which different machining processes can be described. When referring to a machining direction the nomenclature states a labelling system consisting of two numbers. The first number denotes the orientation of the cutting edge to the wood grain direction; the second number denotes the movement of the tool with respect to the grain direction. To illustrate this, the three main cutting directions are listed *(figure 1):*

Corresponding Author** ***Tel: +44 (0) 1912273624
Email: andrew2.naylor@northumbria.ac.uk

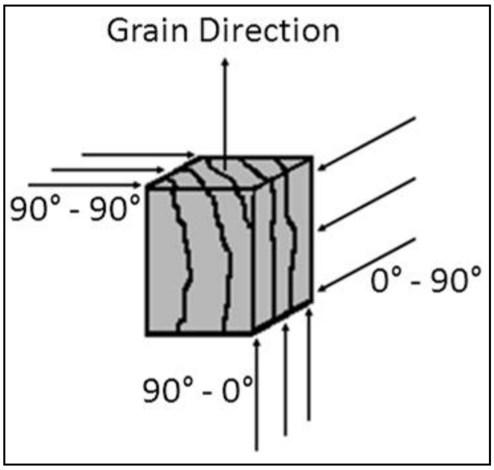

Figure 1 – Machining directions with respect to wood grain

- **90°-90° -** The axial plane or the wood end grain. Both the cutting edge and tool movement are perpendicular to the grain.
- **0°-90°** - The radial and tangential planes, cutting across the grain. The cutting edge is parallel to the grain but the tool movement is perpendicular.
- **90°-0°** - The longitudinal plane, cutting along the grain. The cutting edge is perpendicular to the grain but the tool movement is parallel.

Evidence from fundamental literature [3, 4] suggests that cutting velocity has negligible effect on the forces acting on the tool. This is for the ranges of 0.2 mm/s – 6.3 m/s along the grain and 2.5 m/s – 50 m/s across the grain.

A Review of Planing Operations

Kivmaa [3] used Finish birch in a study investigating the geometric factors of the tool on cutting performance and found that the main cutting force was inversely proportional to the sharpness of the tool. It is also stated at this point that the thrust force is caused by contact between the rake face and the chip. The larger the rake angle the thicker the chip and hence the lower the thrust force. This is because the chip is not being compressed. Although it is observed that there is no significant effect of cutting velocity on the major cutting force, the orientation of the tool with respect to the grain does have a significant effect on the cutting forces. For this planing scenario, the highest cutting forces are observed to be in the 90°-90° direction with the lowest cutting forces in the 90°-0° direction (cutting along the grain). In the same study, the tool sharpness and rake angle remain constant for the testing of 21 different species of wood. Analysis of data found a linear trend between the density of the wood and the major cutting force. From this empirical data a predictive model for cutting force was created.

Extensive work into the chip formation produced through varied cutting conditions has been carried out by Franz [4, 5], McKenzie [6], Woodson and Koch [7]. The cutting tools used in the experiments represent a wood plane that removes material across the entire width of the work-piece. Regarding machining in the 90°-0° direction (along the grain) it was found that large rake angles result in negative thrust forces (acting upwards relative to the work-piece). The wood fibres split ahead of the tool and finally fail due to bending. This type of chip is beneficial where quick removal of material is required. Continuous chip formation is achieved when using a very sharp tool edge and a diagonal plane of shear, providing an excellent surface finish to the work-piece. Dull tool edges, and very small or negative rake angles cause a *fuzzy chip*. It is also suggested that very large depths of cut may form this chip where there is too much contact with the blade surface. This type of chip causes a raised *fuzzy grain* where wood fibres become protruded, hence producing a poor surface finish.

An investigation into the mechanics of cutting across the grain (0°-90°) considers the veneer peeling process as a case study. This process uses high rake angles (approximately 70°) and small depths of cut (less than 1 mm). The material removal in veneer peeling is described as an ongoing shearing process initiated by a tear in compression perpendicular to the grain.

McKenzie [6] investigated the effects of cutting in the 90°-90° direction. In general the cutting mechanics specify a tensile failure mode causing parallel gaps to propagate along the grain. It is noted that these gaps become larger as the moisture content decreases. Cutting forces in this direction are strongly affected by cell type, moisture content, depth of cut, and rake angle

A Review of Single Tooth Operations

The limited research performed on the effects of single point cutting tools focuses on the optimisation of cutting conditions for industrial sawing processes. From the available literature [8-11] it is apparent that the responses desired from experimentation are the forces along the major cutting edge. Chip formation is not heavily investigated.

Machining in the 90°-90° direction, Axelsson [8-10] develops the prior knowledge of the machining process obtained using planing operations by investigating the effects on cutting mechanics using single point cutting tools. For sawing processes, the tool used has a side clearance of 1 mm either side to represent the set of a saw-blade. A grayscale of the wood structure was developed using computerised tomography (CT) where white represents extremely high densities and black represents densities leaning towards zero. For comparison, the cutting force data obtained by the piezoelectric gauges was also converted to grayscale. A linear relationship between the density of the wood for a specified tool path and the cutting forces is established. This is illustrated best cutting through a knot of much higher density to the un-defected wood-grain.

Interesting results were produced from research into the effects of changing the rake angle of band-saw teeth, machining wood in the 90°-90° direction [11]. Three teeth with 25°, 30° and 35° rake angles were examined, it was found that the largest rake angle produced the lowest cutting forces and the smallest rake angle produced the largest cutting forces. Initially, it appeared that the 25° and 35° rake angles produced a smooth work-piece finish after machining, whilst the 30° rake angle produced a rough finish with fuzzy grain. Microscope images showed that the 25° rake angle only appeared smooth when in fact the machining caused fuzzy grain which was then compressed due to the low rake angle of the tooth.

METHODOLOGY

Test Equipment

The experimental test rig comprised of a cutting tool driven by a 3 axis CNC router machine. The work-piece was mounted on a force dynamometer equipped with piezoelectric load cells measuring the cutting, thrust and side force components acting on the tool. Only the cutting and thrust force components were taken into consideration for analysis. The test rig schematic diagram ***(figure 2)*** details the set-up of the data acquisition system. To obtain tool force data, the cutting tool **(1)** was used to machine through the work-piece attached to the force dynamometer **(2)**. The three piezoelectric transducers in the dynamometer each generate a charge in response to the cutting forces (3.9 pC/1 N in X and Y directions, 1.95 pC/1 N in the Z direction). These signals feed into the charge amplifier **(3)** where the signals are calibrated for a 10V input to the data acquisition PLC **(4)** (3900 pC/10 V in X and Y directions, 1950 pC/10 V in Z direction: Hence 1 N = 0.01 V). The PLC converts the signals from analogue to digital and the data can be analysed using appropriate software.

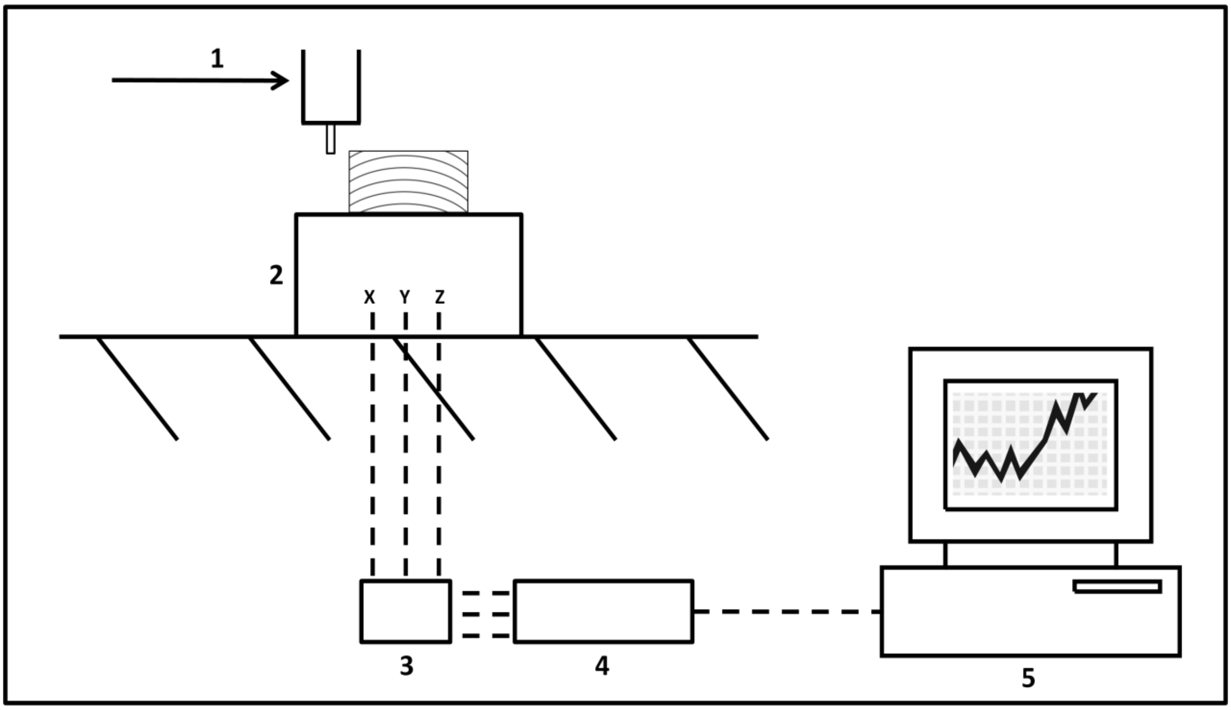

Figure 2 - Test rig schematic with data acquisition system

Experimental design

The tool used in the experiment has geometry similar to the rip tooth formation *(figure 3).* The tool has an orthogonal cutting edge with a width of 1 mm and a rake angle of zero. To ensure that the cutting edge was sharp the tool was sharpened using precision grinding equipment prior to performing the test runs. The two machining directions selected for the experiment were 90°-0° (along the grain) and 0°-90° (across the grain) as these are deemed to be the most common directions for manual wood-sawing.

Eight species of wood where evaluated in the experiment, five softwoods (Scots Pine, Yellow Pine, Siberian Larch, Douglas Fir and Western Red Cedar) and three hardwoods (Ash, Beech and Sapele). Each of these wood species had four separate moisture levels; Dry (<6%), 10%, 20% and Saturated (>30%). Including the two machining directions this amounts to sixty-four work-piece variables. Each of the sixty-four work-piece variations was machined at three depths of cut; 0.4, 0.8 and 1.2 mm, providing a total of one hundred and ninety-two cutting and thrust force values for analysis.

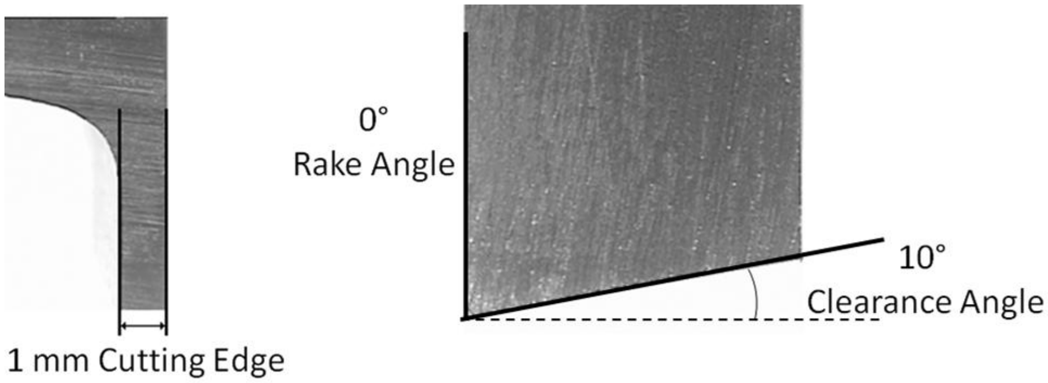

Figure 3 - Optical microscope images of tool

RESULTS AND DISCUSSION

Cutting Force data

For all woods at all moisture levels tested *(figure 4)*, cutting force is observed to increase with depth of cut. Furthermore, cutting across the grain yields higher cutting forces than along the grain. This trend becomes more prominent for increased depth of cut. Thrust force values are also seen to increase with depth of cut. However, wood grain direction is seen to have negligible effect on the magnitude of these forces.

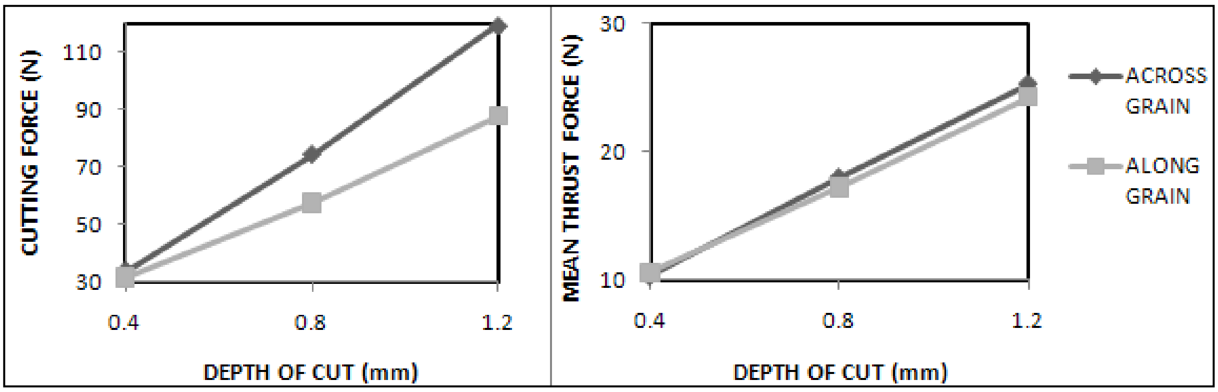

Figure 4 – Cutting/Thrust Force vs. Depth of Cut

When focusing on the average behaviour of all of the woods *(figure 5)*, a linear relationship is observed for the tool forces with regard to moisture content. The highest forces are observed for dry woods and the lowest forces are observed for the saturated woods. The machining direction does not have any significant effect on the thrust force. However, the cutting force is heavily influenced by the machining direction. This is more prominent for increasing depths of cut where machining across the grain yields higher forces than along the grain.

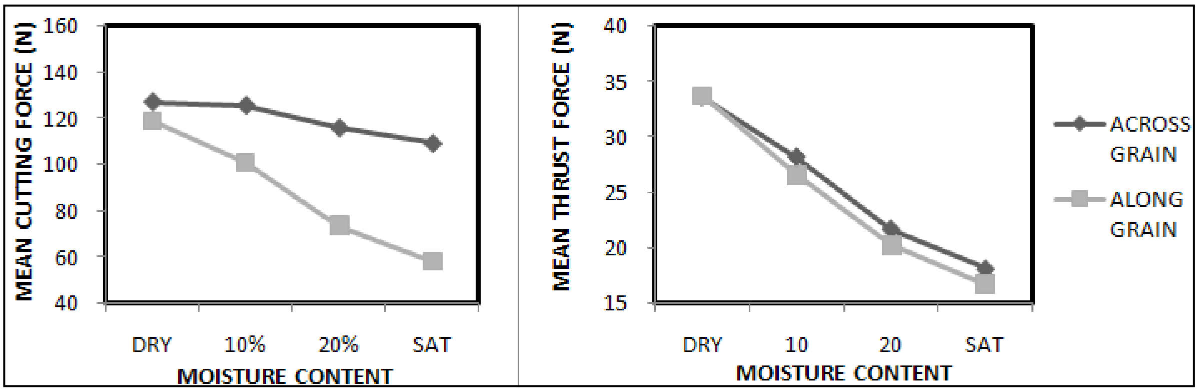

Figure 5 – 1.2 mm depth of cut: Cutting/Thrust Force vs. Moisture Content

When looking at the behaviour of the individual woods *(figure 6)*, certain trends are noticed. In general, the three hardwoods included in the experiment produced higher cutting and thrust forces than the softwoods. One exception to this rule is Siberian Larch which exhibits higher forces along the grain than its other softwood counterparts. It has to be remembered that wood is an anisotropic material. A wood species such as Siberian Larch can yield cutting force responses in one machining direction akin to softwoods, but in the opposite direction can yield forces similar to hardwoods. One explanation for this is the environmental factors associated with the growing conditions of the wood. Siberian Larch grows in extremely cold climates. The extended cold growing season results in the annual growth rings consisting of a larger proportion of the much denser latewood cells. In softwoods growing in the more temperate climates the ratio of earlywood to latewood cells would be approximately 1:1. Any factors attributed to growing conditions can influence the intrinsic properties of the wood.

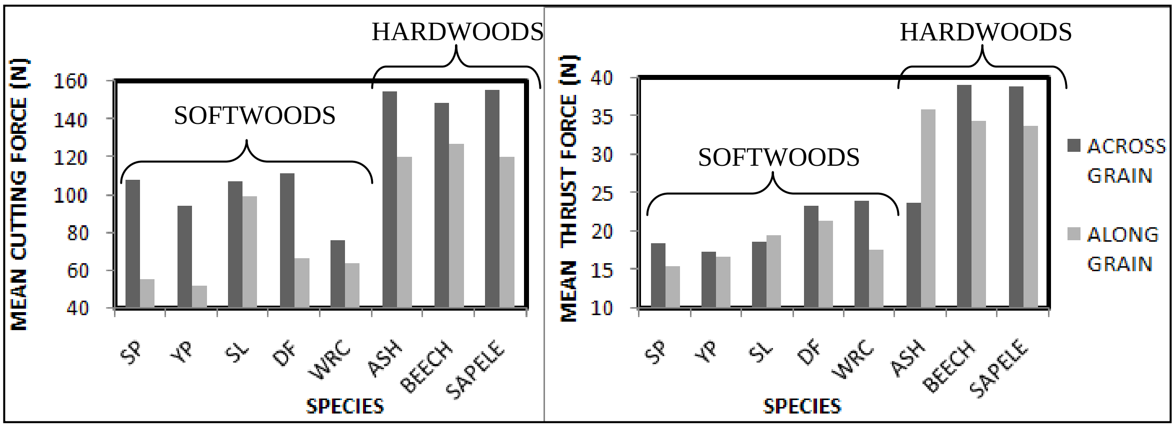

Figure 6 – 1.2 mm depth of cut: Cutting/Thrust Force vs. Species

Chip Formation

Similarities and differences in the chip formed during the rip tooth machining experiment have been compared with results from planing operations [4, 6, 7]. Despite the fact that the rip tooth has zero rake angle all types of chip formation along the grain, as postulated by Franz [4], were observed.

Type I chips were observed for dry wood of all species and depths of cut *(figure 7)*. The chips were discontinuous (broken) and the surface finish of the affected part of the area appeared poor due to several break-off points for the chip.

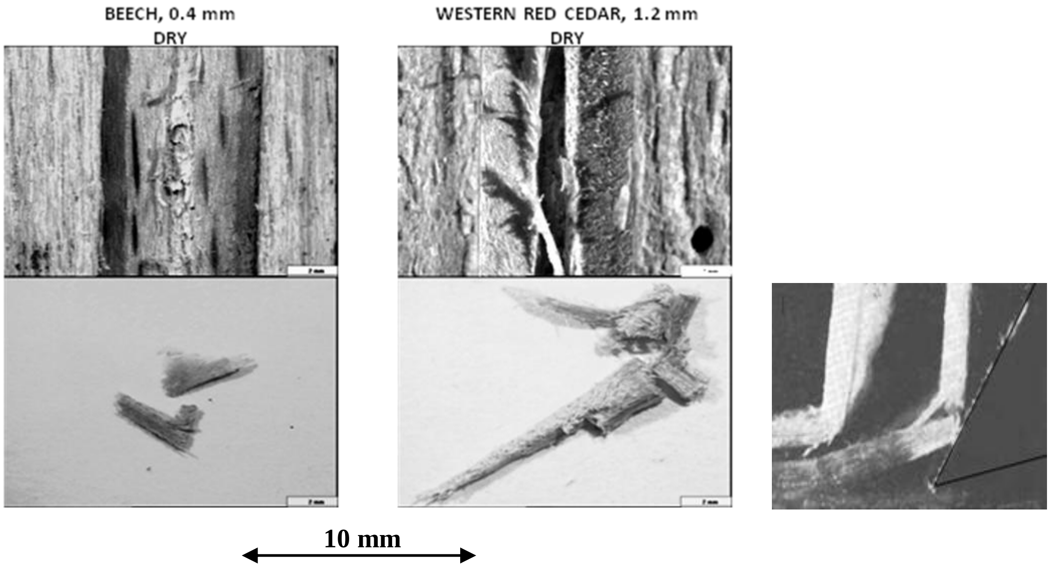

Figure 7 – Type I chip formation along the grain

Type II chip formation occurred at 10-20% moisture content for 0.4-0.8 mm depth of cut as well as for saturated at 0.4 mm depth of cut *(figure 8)*. The area left behind by this formation appeared to have high quality surface finish on account of the continuous (un-broken) chip.

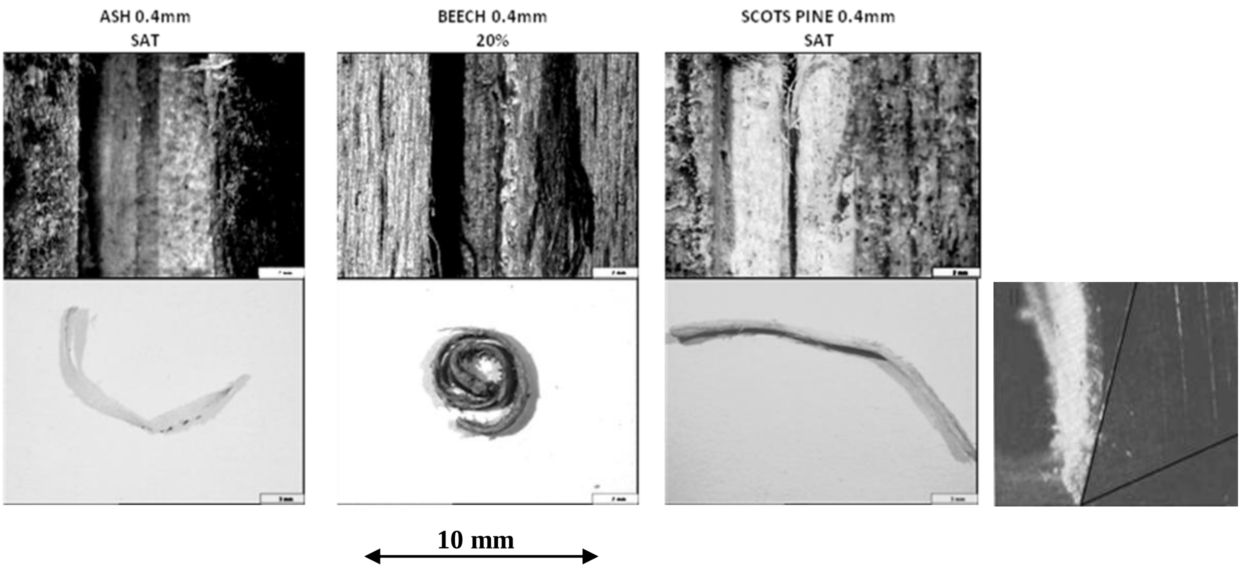

Figure 8 – Type II chip formation along the grain

Type III chip formation occurred mainly for saturated work-pieces (with some occurring at 20% moisture content) at the larger depths of cut of 0.8 and 1.2 mm *(figure 9)*. The surface finish of the work-piece was seen as *fuzzy*, with up-rooted wood fibres left behind in the groove. It is apparent from the microscope images that this type of formation occurred more frequently for softwoods than hardwoods.

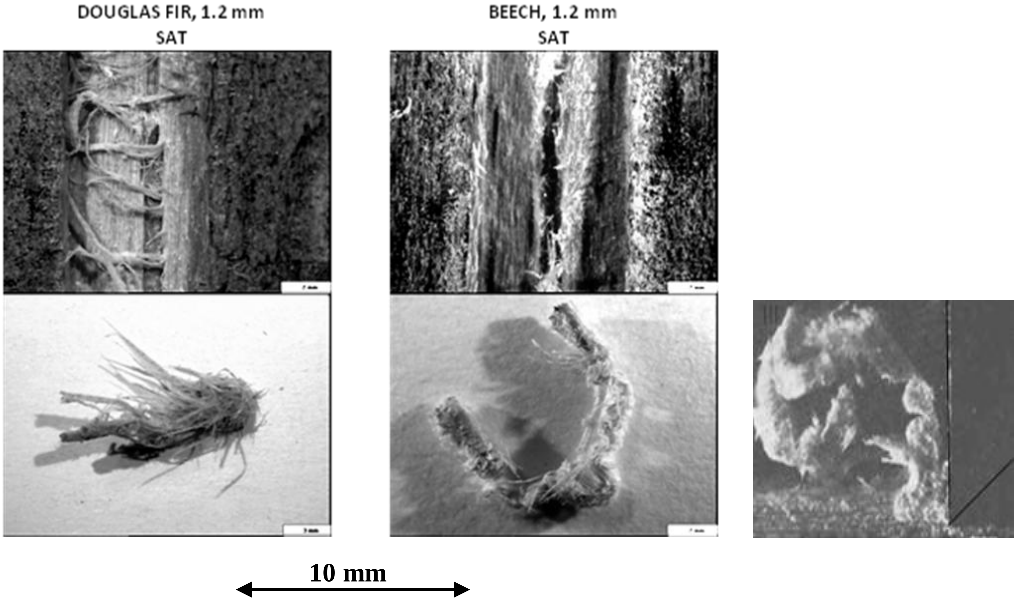

Figure 9 – Type III chip formation along the grain

It has been established that increasing the contact of the tool face by operating with small/negative rake angles and by increasing the depth of cut can cause type III formation (this is exacerbated for rough tool faces). This only occurs for higher moisture contents. In the case of dry woods, the chips start to resemble type I formation. A group of fibres are initially compacted causing a longitudinal crack to propagate in front of the tool. Eventually these fibres shear along the formed crack. Type II formation usually requires a positive rake angle for continuous chip formation. In this instance the reason why this formation is observed is because optimum parameters have been achieved. A combination of optimum moisture content and low depth of cut must be achieved (10-20% at 0.4-0.8 mm and saturated at 0.4 mm) assuming that the tool used has been sharpened.

The work done to previously explain chip formation across the grain does not provide any useful information regarding the rip tooth machining experiment. The main reason for this is because no material removal occurred. Instead the rip tooth ploughed through the wood fibres. Woodson and Koch [7] investigated the mechanics of cutting across the grain for planing tools with large rake angles and concluded that the chip observed is caused by an initial tear in compression followed by ongoing shear. For the rip tooth (which has zero rake angle) the failure mode was observed to be that of bending with no shearing taking place.

To elaborate, bending was observed to be the primary failure mode for all depths of cut. However, the depths of cut that provide better visibility are 0.8 – 1.2 mm *(figure 10).* Work-piece deformation seems to have been greatly affected by moisture content. For dry wood the work-piece appeared greatly deformed with a visible channel down the centre of the tool path. At 10-20% moisture content it is visible that the fibres have been ploughed through. However, there is no channel down the centre of the affected area. For saturated it appeared that even less of the ploughed area was deformed. In some instances it is even hard to see visible evidence that a tool has passed through it. This suggests that higher moisture content causes an increase in the elasticity of the wood fibres. For higher moisture content the fibres break and then attempt to spring back towards the initial position. For dry wood the fibres simply split and remain in that position.

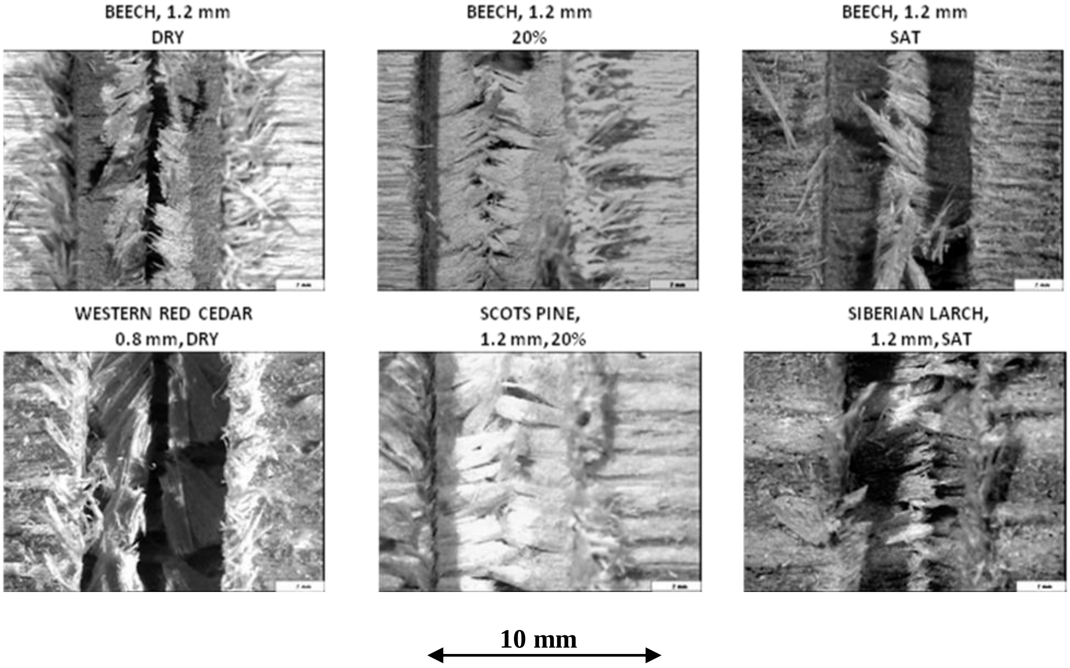

Figure 10 - Observed chip formation across the grain

CONCLUSION

When machining with a single rip tooth the cutting mechanics along the grain consists of an ongoing shearing process which is heavily influenced by moisture content. Dry wood generally requires larger cutting forces to remove material in a stubborn process. This produces chip formation type I, where as saturated wood exhibits liberal material removal at relatively low cutting forces generating chip type III. If chip type II is desirable, parameters for optimum surface finish were observed to be low depths of cut at 10-20% moisture content.

The cutting mechanics across the grain is caused by failure of the wood fibres in bending. The cutting forces across the grain were significantly higher than along the grain. However, there was less difference between dry and saturated average force values. This suggests that the bending effect across the grain was not as significantly affected by moisture content than the shearing effect along the grain. Higher moisture content sees an increase in the elasticity of the wood fibres allowing them to spring back to their original position after ploughing. This however could cause a detrimental effect during the sawing process.

A further programme of work is required to provide complimentary data. ASTM D143-09 standard test procedures for three point bending and longitudinal shear will be implemented to characterize wood strength across and along the grain respectively. Regression analysis will establish a relationship between the collected cutting force data and the obtained mechanical properties (Fracture Stress and Elastic Modulus).

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