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EVALUATION OF HANDSAW TOOTH PERFORMANCE THROUGH THE DEVELOPMENT OF A CONTROLLED CUTTING TEST RIG

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ABSTRACT

In this study a conventional shaper machine has been converted into a controlled cutting test rig. A specially designed tool holder was attached to the actuating arm of the shaper machine. This tool holder constrained a small group of handsaw teeth designed to machine a groove followed by an adjustable single tooth that machined a specified depth of cut. A work-piece dynamometer was attached to the platform of the shaper machine. The three force transducers that compose the dynamometer were used to measure resultant cutting, thrust and side forces in the relative X, Y and Z axes. These are measured as the single tooth passes through the work-piece. In addition to force measurement, a high speed video camera was utilised to capture footage of the chip/surface formation where the tooth interacts with the wood work-piece. The recorded forces and captured footage of chip formation validate published findings that machining along the wood grain is a shearing process and machining across wood the grain is a bending process.

Keywords: Wood Machining, Sawing Processes, High Speed Photography

1 INTRODUCTION

The two parameter groups that influence the cutting mechanics in wood machining are: 1) Parameters associated with the tool geometry, i.e. rake angle, edge width, edge radii etc. 2) Parameters associated with the work-piece, i.e. moisture content, grain direction, physical/mechanical properties etc. The cutting process itself is scrutinised by two separate methods, findings of which can then be combined to make well rounded conclusions. The first method is the measurement of forces acting on the cutting edge of the tool; this is usually done by using force transducers. The second method is the characterisation of chip and surface formation; this can be a simple process of viewing collected chip/surfaces under the microscope or a more sophisticated process of recoding high speed video of the cutting process. The fundamental literature detailing the chip and surface formation across the grain (Franz 1955, Woodson and Koch 1970) details only processes where a large orthogonal tool removes material across the entire work-piece width. This process and the sawing process differ far too greatly to attempt to draw comparisons between the chip/surface formations of the two. From other fundamental literature three distinctive types of chip formation have been observed to occur along the grain (McKenzie 1961). The first type (type I) is caused by a large rake angle producing a negative thrust forces (acting in a positive vertical direction 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. The second type (type II) is formed by a very sharp tool edge and a diagonal plane of shear. Excellent surface finish is achieved due to the continuous chip formation. The third type is caused by dull tool edges, and very small or negative rake angles. 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 third type (type III) of chip causes a raised *fuzzy grain* where wood fibres become protruded, hence a poor surface finish. It is important to note that evidence from the fundamental literature (McKenzie 1961, Woodson and Koch 1970, Franz 1955, Kivemaa 1950) infers that varying the cutting velocity has a negligible effect on the tool forces.

A high speed camera has been previously utilised to capture footage of the cutting process for single circular saw teeth (Ekevad et al. 2011). The camera was set up to record 40,000 frames per second for a circular saw rotating at a speed of 3250 RPM. Green, dry and frozen wood was machined in the 90°-0° direction (along the grain) using single rip teeth with rake angles of 0°, 10°, 20° and 30°. The only observed continuous chip formation (type II) was for green wood, with the dry and frozen work-pieces yielded smaller broken wood particles (type I). Furthermore the footage was able to evaluate the action of the gullet. Reduced rake angle leads to a reduction in gullet volume, still images from this footage show a build up of wood particles for the larger rake angles (lower gullet volume), as the wood chips/particles are prevented from curling past the much smaller root radii. This results in an impaction of wood particles in the gullet impeding the material removal from the kerf.

A study conducted to compare the fundamental chip formation types along the grain to chips formed cutting using a rip saw tooth (Naylor et al. 2011) found that fuzzy chips (type III) occurred machining work-pieces of high moisture content, discontinuous chips (type I) occurred machining dry work-pieces at high depths of cut and the continuous chips (type II) were formed machining dry to moderate moisture content work-pieces at lower depths of cut. Machining across provided no chip for analysis, only a deformed work-piece surface. This surface formation consisted of the fracturing of fibres perpendicular to the grain. Dry work-pieces exhibited a visible tool path with extremely deformed fibres bent out of position. Saturated work-pieces exhibited no visible tool path; this is due to the severed fibres, of increased moisture content, springing back to cover the tool path.

A related study (Naylor et al. 2012) uses properties of the wood obtained through mechanical testing to develop two predictive cutting force models. This study also uses a rip saw tooth of the same geometry as mentioned in the previous paragraph. The first regression model has an R^2 of 90%, it took properties obtained from a three point bending test procedure (used to evaluate the wood strength across the grain) and cutting forces obtained machining across the grain. The second regression model has an R^2 of 80% it took properties obtained from a longitudinal shear test (used to evaluate the wood strength along the grain) and cutting forces obtained machining along the grain.

The aim of the research discussed in this paper was to develop a controlled cutting test rig capable of determining the cutting mechanics for single saw teeth. This aim was facilitated by obtaining footage and still images of the chip formation process to further validate the novel statements regarding the mechanics of cutting; *"cutting along the grain is a shearing process"* and *"cutting across the grain is a bending process"*. High speed footage and optical microscope images were obtained to characterise the chip and surface formation. Tool forces were recorded for varied depth of cut to provide a comparison to the tool forces obtained using the rip tooth in prior related research (Naylor et al. 2011 and 2012).

2 METHODOLOGY

2.1 Single Tooth Test-rig

The saw-tooth geometry selected for the experiment has an orthogonal cutting edge of 0.85 mm, a negative rake angle of 12° and a flank angle of 50° (Figure 1). In industry this tooth geometry is described as a rip tooth due to the low negative rake and lack of bevelled edges that would provide obliquity during cutting. Saws with this type of tooth geometry are typically used only along the grain with each tooth removing material in a chisel like action. In this study machining took place both along and across the wood grain for only one species (douglas fir).

A conventional shaper machine was procured to perform a linear cutting action using selected handsaw teeth (Figure 2.A). The simplified test rig schematic (Figure 2.B) shows the basics of how the tool forces were measured. The cutting tool (1) passed through the work-piece clamped to the dynamometer. The dynamometer platform fed into the cutting tool in even increments for each stroke (2).

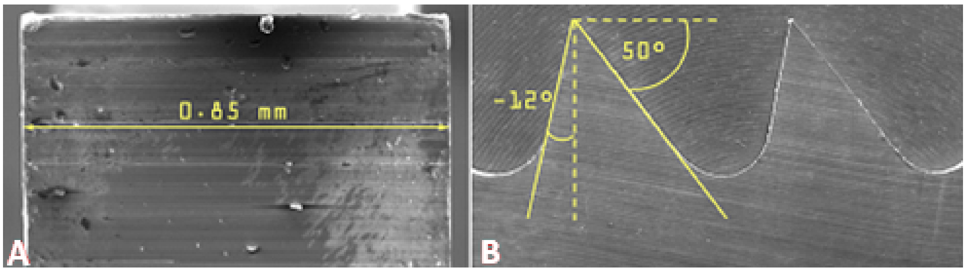

Figure 1: A) Edge Width: B) Rake and Flank of Tooth

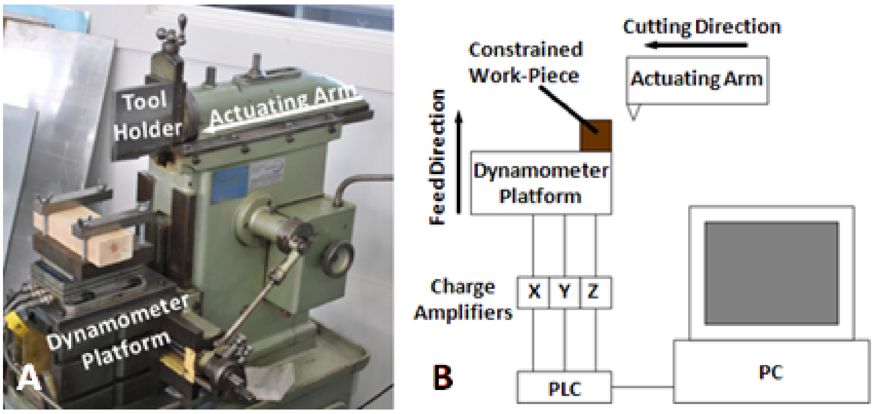

Figure 2: A) Shaper Machine Set-Up: B) Detailed Test-Rig Schematic

The forces applied to the work-piece stimulated a charge output from the transducers which then channelled through to the charge amplifiers (3). These amplified values were converted from analogue to digital (4) and finally were recorded on the PC (5). To elaborate, the dynamometer consisted of three piezoelectric transducers measuring forces in the x, y and z directions. The x and y axes transducers had a sensitivity of 7.5 pC/N and could measure up to 5 kN of force. The z axis had a sensitivity of 3.7 pC/N and could measure up to 10 kN of force. The signal output from each transducer was channelled into an analogue charge amplifier (one amplifier per transducer). The input sensitivity was calibrated to match the transducer sensitivity (in pC) and the output range was set to 100 N = 1 V up to a maximum output of 10 V (1 kN). The output from the charge amplifier was then sent to a data acquisition PLC, converting the analogue signal to digital allowing the forces to be recorded on a PC using LabView signal express.

2.2 Recording High Speed Video Footage

A high speed camera capable of recording 1000 frames per second was acquired for this experiment. A group of four teeth were used to perform the cut. This group of teeth was inclined in the tool holder at 3° ensuring that each tooth performed a depth of 0.15 mm (based on a pitch of 7 teeth per 25 mm). Cutting was performed along and across the wood grain for both dry and saturated work-pieces. Typically the first tooth would perform little to no cutting with the second tooth performing the first cut. Subsequently the third and fourth teeth would each machine at a depth of 0.15 mm visible to the camera.

2.3 Single Tooth Tests

Tests performed using only single teeth were not recorded using the high speed camera. This was because most of the tooth was obscured from view by a prior machined groove. The purpose of the groove was to provide a level cutting surface parallel to the tool path ensuring that a constant depth of cut was maintain for the entire work-piece surface. Depths of cut of 0, 0.05, 0.15, 0.2, 0.25, 0.3, 0.35 mm were performed along and across the wood grain for both dry and saturated work-pieces. The offset between the single tooth and the prior machined groove was controlled using feeler gauges ensuring an accurate depth of cut.

3 RESULTS

3.1 Chip Formation

Machining the dry work-piece along the grain yielded continuously formed, unbroken wood chips and a cleanly cut surface. In contrast to this, machining the saturated work-piece along the grain yielded fuzzy chips. It is apparent from the high speed video frames that the wood fibres in these chips disintegrated when removed from the work-piece surface by the saw tooth. Furthermore, similar disintegrated wood fibres were left behind on the surface.

Initial deformation perpendicular to the grain is observed in the high speed video frames when machining the dry work-piece across the grain. This was followed by an instantaneous failure and more aggressive cutting process from the following teeth. Machining the saturated work-piece across the grain exhibits a less aggressive cutting process. It is apparent from the frame by frame analysis that these fibres are initially deformed in a similar way to the dry work-piece. The fibres spring back towards the tool path and are subsequently removed from the surface. It must be noted that the tooth that initially makes contact with these fibres is only performing a ploughing action; the uprooting effect is caused by teeth that follow.

3.2 Tool Forces

The mean tool forces (Figure 5B) combine all work-piece conditions to provide average response data for cutting, thrust and side forces. The magnitudes of the thrust forces are approximately 12% the magnitude of the cutting forces, for all depths of cut (i.e. the thrust forces are proportional to the cutting forces as they both increase with depths of cut). The side forces exhibit no noticeable trend for increasing depths of cut with magnitudes ranging from 2 to 5 % of that of the cutting forces.

When evaluating the measured cutting forces for all work-piece variations (Figure 5A) a few trends are noticed. On average machining along the grain yields approximately half the cutting force observed across the grain. Machining saturated work-pieces yields lower cutting forces; in the range of 70 – 80 % of the values observed for the dry work-pieces (this excludes 0 and 0.05 mm depth of cut for saturated, across the grain, which are slightly larger force values than observed for dry, across the grain). In summary, the cutting forces for the different work-piece conditions all have the same linear trend with respect to depth of cut. The only thing that differs between the different work-pieces is the magnitude of the forces.

4 DISCUSSION

4.1 Chip Formation

The chip and surface formation observed draw similarities to formations observed from fundamental literature (McKenzie 1961) and previous study where a single rip saw tooth was used (Naylor et al. 2011). Machining the dry work-piece along the grain forms continuous chips (type II) and machining the saturated work-piece along the grain forms fuzzy chips (type III). No discontinuous chips (type I) were formed as only the relatively low depth of 0.15 mm was performed. Surface formation machining across the grain also draws some similarities to the previous study. The surface formation of the dry work-piece displays permanently deformed fibres with a visible tool path. The surface formation of the saturated

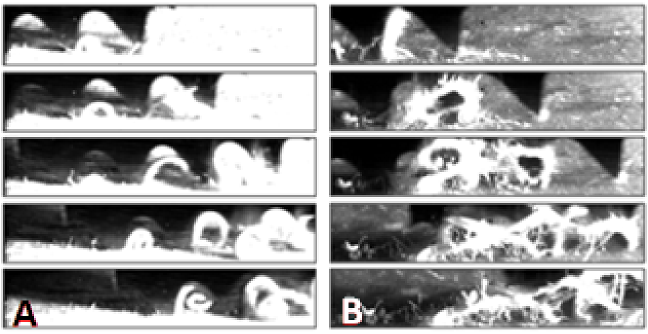

Figure 3: A) Chip Formation Along the Grain, Dry; B) Along the Grain, Saturated

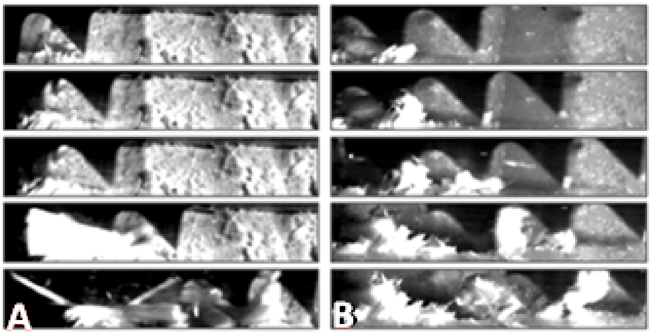

Figure 4: A) Surface Formation Across the Grain, Dry; B) Across the Grain, Saturated

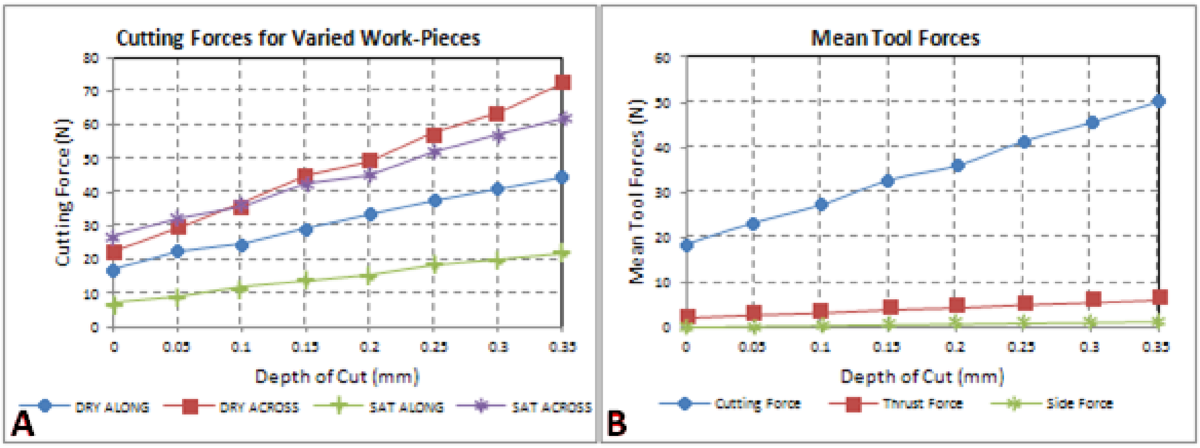

Figure 5: A) Cutting Force vs. Depth of Cut for all Work-piece's; B) Mean Tool Forces vs. Depth of Cut

work-piece shows some sections along the length of the kerf were fibres have sprung back over the tool path, but other sections where fibres have been uprooted by the subsequent teeth in the group. No major chip formation comparisons can be drawn to the circular saw study (Ekevad et al. 2011), which also used high speed video footage to analyse the chip. The reasons for this are the difference in work-piece (**1**) (the circular saw study uses green and frozen wood) and a focus on the gullet performance rather than the interaction with the wood and the major cutting edge (**2**). A key difference is noticed for machining dry work-pieces along the grain, which yielded discontinuous wood chips (type I). This is most probably due to the circular saw tooth geometries which have large positive rake angles.

4.2 Tool Forces

From prior research (Naylor et al. 2011 and 2012) average tool force values show that the cutting force is approximately 4.5 times larger than the thrust force and 25 times larger than the side force across the grain. Along the grain the cutting force is approximately 3.5 times larger than the thrust force and 10 times larger than the side force. Analysis of the mean tool forces in this study (combining both along and across the grain) show the cutting force to be approximately 8 times larger than the thrust force and in the range of 20 – 50 times larger than the side force. This discrepancy is due to the difference in tooth geometry and cutting conditions. The geometry of the tooth used in prior research had zero rake and a 1 mm cutting edge. The geometry of the tooth used in this research had a negative rake of 15° and a 0.85 mm cutting edge. Furthermore the depths of cut performed in the prior research where in the range of 0.4 – 1.2 mm. The depth of cut range used in this study was much lower, 0 – 0.35 mm.

4.3 A Statement on the Mechanics of Cutting

It is important to note that the high speed video footage provides frame by frame evidence to support findings from related research (Naylor et al. 2012). The statement that machining along the grain is a shearing process is supported by the visible shearing action providing ongoing continuous formation with no break off points. The statement that machining across the grain is a bending process is supported by the high speed video showing the fibres deforming in a bending process prior to fracture.

5 CONCLUSION

It has been proven that the test rig developed can effectively evaluate the cutting mechanics for single saw teeth. This has been demonstrated through the high speed recordings of chip formation and the tool force measurements. The most significant of the measured tool forces is that in the direction of cutting ranging from 20 – 50 N (based on an average of all work-piece variations). The thrust force is less significant, approximately 12% of the cutting force. The side force is the least significant force with recorded values under 5% the magnitude of the cutting forces. The cutting force values show that the different work-piece variations all have the same linear trend with respect to depth of cut; only the magnitude of the forces varies. Typically cutting dry work-pieces yielded higher forces than saturated work-pieces, cutting across the grain yielded higher forces than cutting along the grain.

The still frames from the high speed video of the chip and surface formations provided supporting evidence to two novel statements with regard to the mechanics of cutting using teeth with orthogonal edges: 1) *Cutting across the grain is a bending process;* 2) *Cutting along the grain is a shearing process.*

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