Operational performance of individual handsaw teeth

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ABSTRACT

Initially a study was conducted using a single ripsaw tooth to cut a variety of woods both along and across the grain. A CNC router machine was used to control the tool path and apply cutting depths of between 0.4-1.2 mm. A series of mechanical tests were conducted concurrently, evaluating the same wood varieties in bending (across the grain) and shear (along the grain). A second study evaluated two different tooth geometries: a bevelled handsaw tooth and an unbevelled handsaw tooth. In this instance only one wood variety was machined (Douglas fir) both along and across the grain. To ensure a lower cutting depth (≈0.15 mm) a shaper machine was used to control the tool path. A high speed camera with macroscopic lens was used to capture the chip formation in real time. For the first study, a triaxial dynamometer was used to record the forces acting on the ripsaw tooth. Modulus of rupture (Pa) and bending toughness (J/m^3) were found to have the greatest influence on cutting forces across the grain. Likewise, shear strength (Pa) and shear toughness (J/m^3) were found to have the greatest influence on cutting forces along the grain. From the second study, the high speed footage of the unbevelled handsaw tooth showed this to be the most effective at removing material along the grain in a “chisel like” cutting action. The high speed footage of the bevelled handsaw tooth showed that the sharp lateral edges of these teeth are ideal for severing the wood fibres across the grain in a “knife like” cutting action.

Keywords: Cutting Force; Regression Analysis; Chip Morphology

INTRODUCTION

Since the earliest scholarly studies around wood machining (Franz, 1958, Kivimaa, 1950, McKenzie, 1961, Woodson and Koch, 1970), the mechanics of the cutting process has been evaluated by two archetypal methods: 1) measurement of forces acting on the tool; 2) qualitative analysis of the chip formation. These early studies used large orthogonal cutting tools, machining at high cutting depths, making it relatively easy to capture images of chip formation using contemporary photographic methods. More recently, high speed video recording has been implemented to capture footage of wood machining using saw teeth (Ekevad et al., 2012) allowing for real time analysis of the chip formation process.

Tool forces are invariably measured using one or more piezoelectric transducers, in many instances with three arranged in the relative x, y and z directions as a triaxial dynamometer. Regression analysis has been used to develop predictive cutting force models for simple rip tooth geometries (Axelsson et al., 1993, Cristóvão et al., 2012, Lhate et al., 2011). In general, the geometric parameters (rake angle and edge radius) were used as model predictors. Only a limited number of workpiece properties (density and moisture content) were used as model predictors.

The work detailed in this present study is derived from the lead authors doctoral thesis (Naylor, 2012). It provides further commentary and analysis on the use of mechanical properties as predictors in cutting force models (Naylor et al., 2012c); and high speed video analysis of handsaw tooth cutting mechanics (Naylor, 2014).

MATERIALS AND METHODS

In the initial study (study 1), the cutting action was performed using a ripsaw tooth with a 1 mm orthogonal edge. The tool path and cutting depth was controlled using a CNC router machine. As cutting speed is known to have little influence over the tool forces (Kivimaa, 1950, McKenzie, 1961), a relatively low cutting speed of 100 mm/s was justified. For each cut performed, a Kistler 9377C triaxial force dynamometer (Kistler Group, Winterthur, Switzerland) was used to measure the force in the direction of cutting (cutting force); the force normal to the direction of cutting (thrust force); and the force acting on the side of the ripsaw tooth (side force).

Eight different species of wood were used (Yellow pine; Scots pine; Western red cedar; Douglas fir; Siberian larch; Ash; Beech; and Sapele) all with varying moisture content and mechanical properties. These properties, and the associated mechanical test procedures, were taken from a separate log (Naylor et al., 2012a). To paraphrase, the ASTM three point bending procedure (American Society for Testing and Materials, 2009) was used to determine the modulus of elasticity (***MOE***) Pa, modulus of rupture (***MOR***) Pa, and flexural toughness ($\boldsymbol{U_b}$) J/m^3. The shear test methodology was also ASTM standard (American Society for Testing and Materials, 2009) which was used to determine the shear elastic modulus (**G**) Pa: shear strength ($\boldsymbol{\tau}$) Pa; and shear toughness ($\boldsymbol{U_s}$) J/m^3. Further to this, density ($\boldsymbol{\rho}$) kg/m^3 was measured gravimetrically, and moisture content was determined using a protimeter.

A full factorial experimental design was carried out, in which the eight different species of wood were machined both along and across the grain; with four nominal moisture levels (dry, 10%, 20% and saturated); with three cutting depths (0.4, 0.8 and 1.2 mm). This provided 192 cutting, thrust and side forces for further analysis.

To evaluate the chip formation process in real time, a second study (study 2) was carried out, with the protocol detailed in a previous report (Naylor et al., 2012b). In this study a high speed camera recorded footage of the cutting process at a rate of 10,000 frames per second, similar to the methods employed by Ekevad et al (Ekevad et al., 2012). The two geometries of handsaw tooth selected (Figure 1) were ground onto 0.8 mm high speed steel. One of these teeth was bevelled with a negative rake angle of 15° and a bevel angle of 28°; whilst the other was unbevelled tooth with a negative rake angle of 13°. To ensure a controlled cutting depth of 0.15 mm (typical depth per tooth for manual sawing), a shaper machine with a stiff vertical axis was employed in place of the milling machine used for study 1. For each recording, a group of teeth was inclined at an angle in the tool holder, with 0.15 mm feeler gauges used to dictate the vertical offset between each tooth. To limit the influence of workpiece properties on chip formation only one species of wood was selected (Douglas fir).

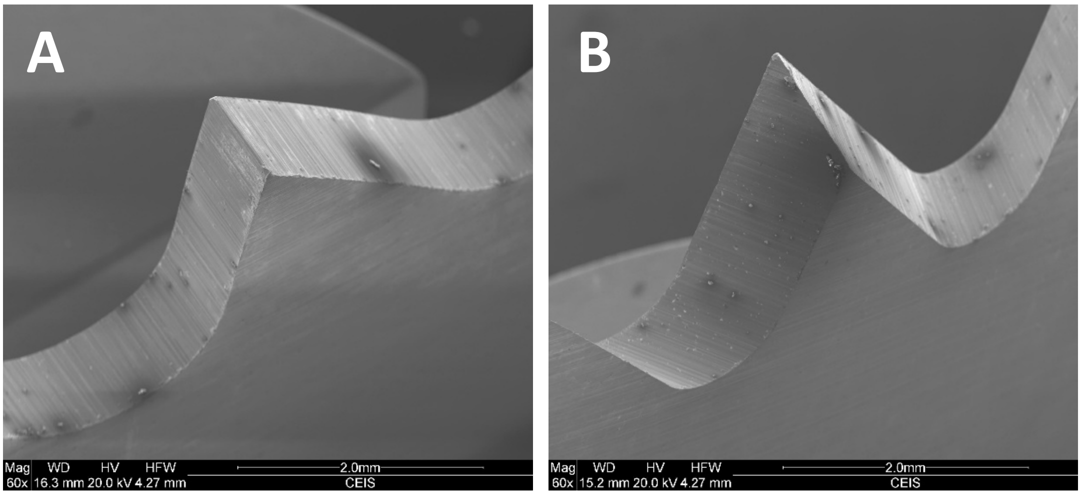


Figure 1: Micrograph images of the unbevelled handsaw tooth (A); and the bevelled handsaw tooth (B)

RESULTS AND DISCUSSION

After completing study 1, a notable disparity between the cutting, thrust and side forces was manifest (Figure 2). Student's t-test was carried out to discriminate the forces for along vs. across the grain. A significant difference was noted for the cutting force values ($p=0.007$): with 58.4 N and 74.7 N along and across the grain respectively. There was no significant difference in the thrust force values ($p=0.727$): with 17.36 N and 17.89 N along and across the grain respectively. Likewise, there was no significant difference in the side force values (p=0.062): with 1.86 N and 2.34 N along and across the grain respectively. En masse, the cutting force values were more than three times greater than thrust force values; and over thirty times greater than side force values. At this point it was deemed prudent to focus only on the cutting force values when carrying out further analysis.

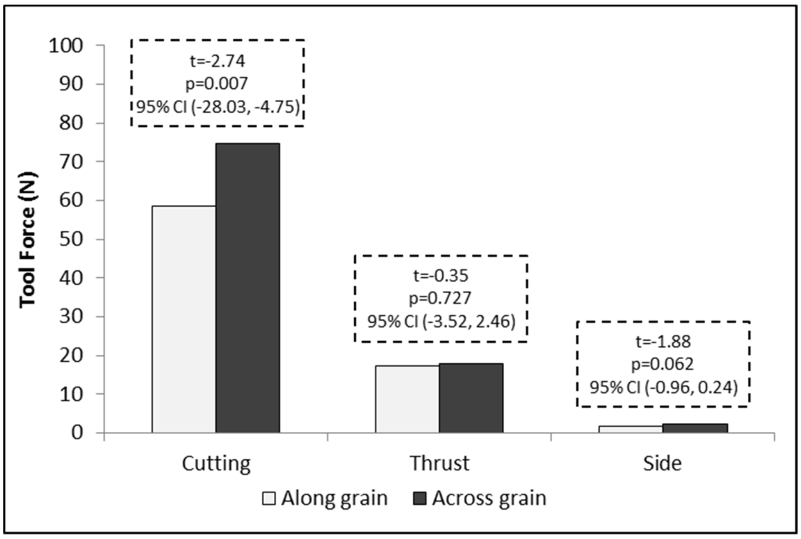
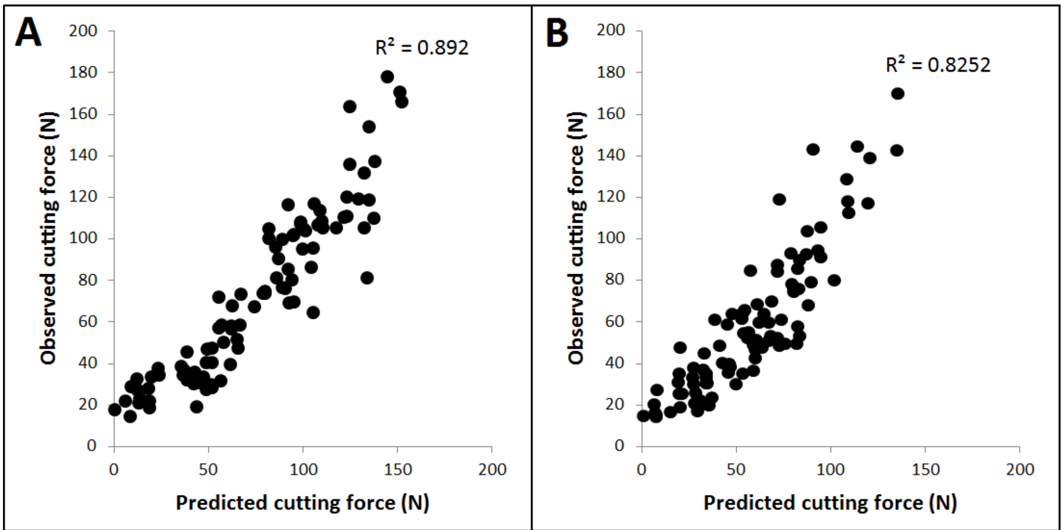


Figure 2: Mean cutting; thrust; and side forces (N) along and across the grain, displayed with Student's t-test results (dashed border).

Density, moisture content and cutting depth were used as predictors in both multiple regression models (Figure 3). In addition to these, properties obtained across the grain (***MOR***, ***MOE*** and $\boldsymbol{U_b}$) were used as predictors for model **F∟**; and properties obtained along the grain ($\boldsymbol{\tau}$, ***G*** and $\boldsymbol{U_s}$) were used as predictors for model **F||**.



$F\llcorner = -72.7 - 0.000093\boldsymbol{MOE} + 0.235\boldsymbol{MOR} + 0.0594\boldsymbol{\rho} + 108\boldsymbol{\delta} - 0.129\boldsymbol{MC} + 0.00526\boldsymbol{U_b}$	$F\|\| = -15.3 - 0.0243\boldsymbol{G} + 0.235\boldsymbol{\tau} + 0.0264\boldsymbol{\rho} + 65.4\boldsymbol{\delta} - 0.301\boldsymbol{MC} + 0.00492\boldsymbol{U_s}$

Figure 3: Predictive cutting force models machining across (A) and along (B) the grain, displayed with regression equations.

Both models demonstrated a good fit with R^2=0.892 and R^2=0.825 for **F∟** and **F||** respectively. Although the regression equations (Figure 3) are of some use, the coefficients may appear misleading. This is due to the order of magnitude of the categorical predictors used. For instance, take the elastic properties (***MOE*** and ***G***) compared with the strength values (***MOR*** and ***τ***). These were input into the two models as Pa (not MPa, nor GPa). Elastic properties for wood are typically three orders of magnitude greater than strength values. This undoubtedly inflated the coefficients of the strength values, whilst making the coefficients of the elastic properties seem small by comparison. This does not necessarily mean that the elastic properties have less of an influence over the predicted cutting forces than the strength values. In order to properly evaluate the influence of ***MOR***; ***MOE***; U_b; and ***ρ*** for model **F∟**, as well as ***τ***, ***G***; U_s; and ***ρ*** for model **F||**, one way analysis of variance (ANOVA) was carried out for each predictor. From ANOVA, the F statistic was calculated and used to compare the influence of each predictor (Figure 4). This analysis showed both the toughness and strength values to have more influence on the cutting forces. The elastic properties had less influence on the cutting forces, but certainly not as little as the regression equation coefficients would lead one to assume. Interestingly, density had less influence on cutting forces along the grain than across. This is because the saw-tooth machined through dense earlywood and less dense latewood fibres in equal measure when machining across the grain. There was no way to ensure that the saw-tooth cut through exactly the same proportion of earlywood and latewood fibres when machining along the grain.

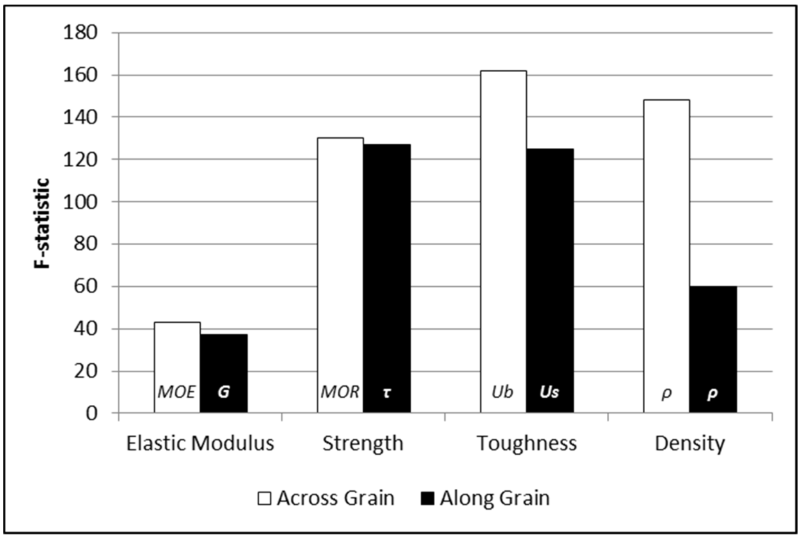


Figure 4: F-statistics obtained from one way ANOVA weighing the effects of elastic properties; strength values, toughness and density on respective cutting force models.

The unbevelled tooth, observed during study 2, most closely resembles the rip tooth used to perform the cutting action in study 1. Stills from the high speed video footage (Figure 5A) show the orthogonal cutting edge *shearing* the wood fibres along the grain, with the gullet effectively removing the chip from the kerf. By contrast, the gullet of the bevelled tooth does not effectively remove the chip from the kerf (Figure 5C). Instead, the chip can be seen being pushed into the wall of the kerf normal to the 28° bevel angle. When cutting across the grain (Figure 5B), the unbevelled tooth is seen to *bend* the first row of fibres prior to fracture. The sharp lateral edge of the bevelled tooth severs the fibres, with little bending observed prior to fracture (Figure 5D).

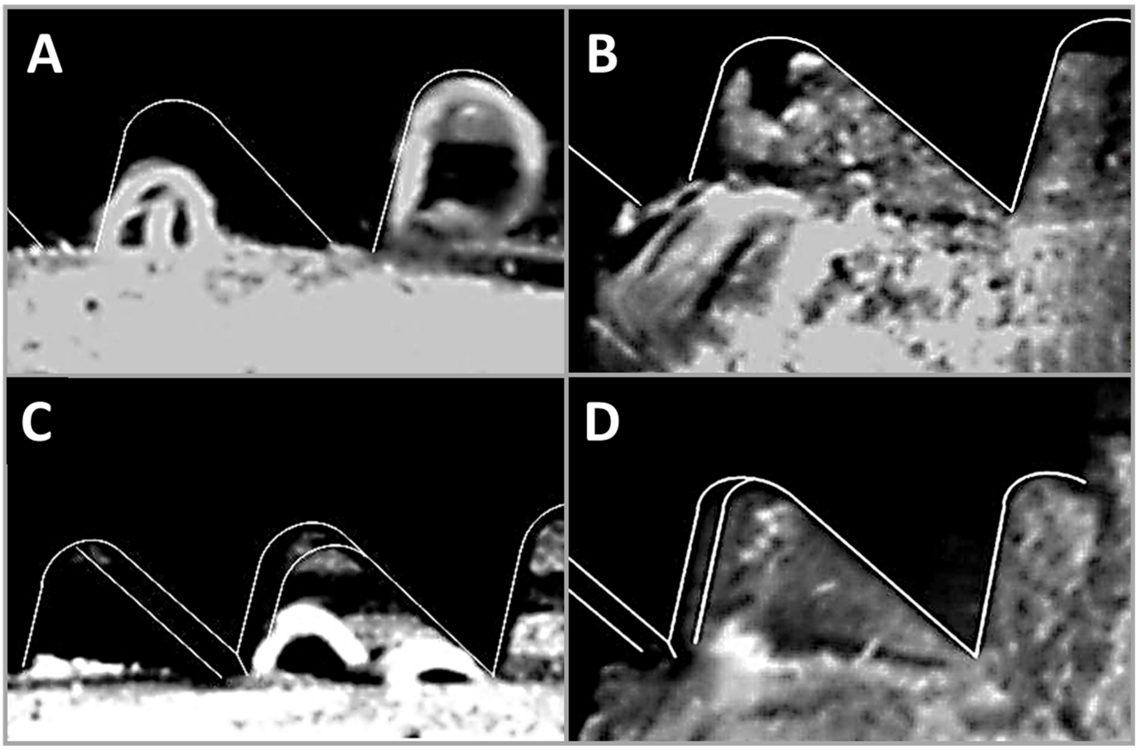


Figure 5: Stills from high speed video footage showing: unbevelled tooth along the grain (A); unbevelled tooth across the grain (B); bevelled tooth along the grain (C); bevelled tooth across the grain (D)

CONCLUSIONS

The multiple regression models demonstrate a strong relationship between mechanical properties of wood and the cutting forces. Modulus of rupture, bending toughness and density have the most influence on the cutting forces when machining across the grain. Shear strength and shear toughness have the most influence on the cutting forces when machining along the grain. Neither modulus of elasticity in bending nor in shear had much influence over the cutting forces across and along the grain respectively. High speed footage of both the bevelled and unbevelled handsaw teeth shows continuous chip formation along the grain, analogous to "chiseling" and indicative of a shear failure mode. The high speed footage of the unbevelled tooth across the grain shows visible evidence of the fibers bending prior to fracture. This is less evident for the bevelled tooth, where there is less bending visible prior to fracture in more of a "knife cutting" action.

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