A Review of Wood Machining Literature with a Special Focus on Sawing

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In this review, fundamental wood machining research is evaluated to determine the general cutting mechanics of simple, orthogonal, and oblique cutting tools. Simple tool force trends and chip formation characteristics are indentified here, along with the cause and effects of tool wear. In addition to this, specific methods of evaluating sawing processes have been investigated. These include the use of piezoelectric dynamometers to record tool forces and high speed photography to evaluate chip formation. Furthermore, regression analysis has been previously used to identify tool force trends with respect to both tooth geometry parameters and work-piece properties. This review has identified the original findings of previous research. This will allow for further original research to be conducted.

Keywords: Wood Machining; Tool Forces; Tool Wear; Sawing

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INTRODUCTION

Throughout history the handsaw has proven to be one of the most widely used hand tools. This dates back to the first flint saws used during the Neolithic revolution *circa* 9500 BC (Jones and Simons 1961). In subsequent eras the technology continued to advance through the bronze and iron ages. Applications of the hand saws widened through the Roman era, where they became increasingly used in construction and even as a method of execution (Suetonius-Tranquillus, AD 119). The closed handle handsaw that we recognize today has its origins at the turn of the 18th century. Prior to this, saws with an open handle or “pistol grip” were the norm. The teeth were manually filed and set using a small hammer and anvil. In the developing world, where carpenters see their tools as an investment rather than a replaceable good, this method is still widely used. The saw teeth are re-set and filed when the edges become too worn for functional use, thus increasing the life of the saw. Since the latter part of the 20th century, the developed world has opted for hardened saw teeth. This is achieved by inducing an electromagnetic field at the edge of the blade heating the steel and hence forcing martensitic transformation. This makes the saw teeth extremely resilient to tool wear, removing the need to re-sharpen. Additionally, grinding and setting are fully automated processes.

Research performed into optimum wood machining conditions (Eyma *et al.* 2004; Méausoone 2001) states that there are generally three types of factors that affect the cutting mechanics:

1. Factors attributed to the machining process
2. Factors associated with wood species/intrinsic properties

3. The moisture content of the wood

Analysis of the wood cutting process in the published literature (Franz 1958; Kivimaa 1950; Koch 1964; McKenzie 1961) examines these three effects, with publications investigating defects in the wood grain such as knots (Axelsson 1994).

Wood has three planes of symmetry; axial, radial, and tangential. Corresponding to these planes of symmetry are the cutting directions by which machining processes can be described (Fig. 1). When referring to a machining direction, the established labeling system employs two numbers separated by a hyphen. 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:

- 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.

Previous research into wood-cutting mechanics investigated machining parallel and perpendicular to the grain (Axelsson 1993, 1994; Franz 1955, 1958; Huang 1994; Koch 1964; McKenzie 1961; Woodson and Koch 1970). Additionally, more recent studies have investigated the effects of cutting across the grain at various angles with and against the annual growth rings (Costes *et al.* 2004; Goli *et al.* 2002b, 2003, 2005, 2009).

Contrary to wood machining, a significant volume of research has been performed in the area of metal cutting, the most fundamental of which describe it as a plastic deformation process of an isotropic material (Ernst 1938; Merchant 1944). Wood is a material that is both heterogeneous and anisotropic, making it very unpredictable during

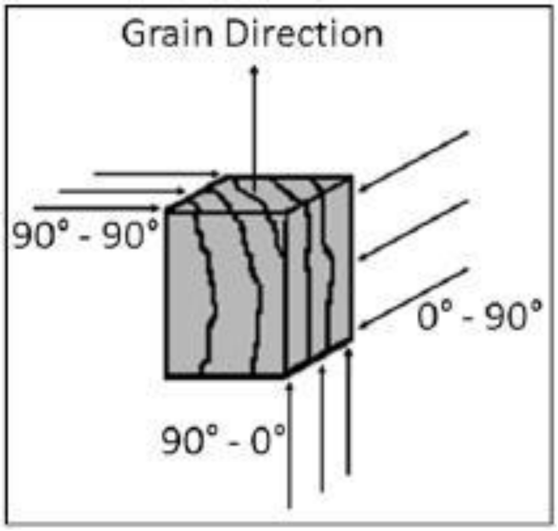

Fig. 1. Wood machining directions

any machining process. On a macroscopic level, wood gains its non-uniform structure from its concentric annual growth rings composed of earlywood cells (formed during the darker, cooler spring months) and latewood cells (formed during the warmer, lighter summer months). These cells grow longitudinally through the trunk of the tree. Additionally, wood contains knots where limbs grow out from the trunk; these weaken wood as a material as they are poorly bonded to the surface which surrounds them.

THE PLAINING PROCESS

Orthogonal Plaining

Plaining is a process by which a knife edge removes a layer of material on the top surface of a work-piece. As there is clearly material removal in the form of chip or swarf, analysis of the chip formation is often used to characterize the process. Early research into the metal-cutting process by Ernst (1938), Merchant (1944), and Lee and Shaffer (1951) has established relationships between the cutting conditions and the deformed chip. These relationships have successfully explained the process as *plastic deformation* of an *isotropic* material. As wood is an *anisotropic* material, chip formation changes with respect to the machining direction.

The first comprehensive investigation into wood machining (Kivimaa 1950) investigated the effects of varying tool geometry and species factors for plaining operations. In experimental work evaluating the cutting action of the tool, the work-piece properties were not varied, standardizing on Finnish birch as the sole species. It was found that the main cutting force was inversely proportional to the sharpness of the tool, *i.e.* the sharper the tool, the lower the force. It also can be stated at this point that the thrust force is caused by contact between the rake face and the chip. Larger rake angles result in greater chip thickness hence lower thrust force. This is because the chip is not being compressed at the extreme cutting edge. 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. The highest cutting forces are observed to be in the 90°-90° direction (wood end grain), with the lowest cutting forces in the 90°-0° direction (cutting along the grain).

In other experimental work (Axelsson *et al.* 2003) 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.

For orthogonal wood cutting, extensive work into the chip formation produced through varied cutting conditions has been carried out by Franz (1955, 1958), McKenzie (1961), and Woodson and Koch (Koch 1964; Woodson and Koch 1970). The cutting tools used in the experiments represent a planing tool that removes material across the entire width of the work-piece. This set-up typically consists of the tool being attached to a strain gauge rosette (measuring cutting and thrust force components). Cutting along the grain gives three types of characterized chip (Fig. 2):

- Type I chip is caused by a large rake angle producing 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.

- Type II chip 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.
- Type III chip 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 type of chip causes a raised *fuzzy grain* where wood fibres protrude, hence a poor surface finish.

Further work done by Woodson and Koch (1970) cutting across the grain demonstrates that higher moisture contents increase the length of chip type II before failure. The forces observed in the latewood fibers are approximately double that of the earlywood fibers with a positive correlation between cutting force and moisture content. The same publication documents the effects of cutting across the grain in what is described as the *veneer peeling* process. This process uses high rake angles (approximately 70°) and small depth of cut (less than 1 mm) with a *nosebar* used to compress the cells before cutting to ensure that the veneer remains a single unbroken sheet. The chip is formed by an initial compaction of the wood fibres (3) followed by an ongoing shearing process (2) with some tensile failure also observed (1) (Fig. 3). This form of cutting results in higher forces and discontinuous chip compared to veneer peeling. Cutting forces for ealywood and latewood in this direction are the same.

McKenzie (1961) investigated the effects of cutting across the grain and discovered two distinct chip types (Fig. 4). Type I is typical for cutting wood with a very high moisture content and type II for low moisture content. The cutting mechanics for both conditions specify a tensile failure mode causing parallel gaps to propagate between the fibers; however, these gaps become larger with decreased moisture content. Cutting forces in this direction are strongly affected by cell type, moisture content, depth of cut, and rake angle, where the values of the cutting force for latewood are approximately three times the values for earlywood.

Further research (Goli *et al*. 2001a, 2002a,b, 2003, 2005, 2009) delves into the change in cutting mechanics when machining at different orientations with respect to the grain. The grain orientation that provides the highest forces and leaves behind the most protruded distorted grain is cutting in the 90°-90° direction (Goli *et al.* 2005). As previously discovered by Kivimaa (1950), cutting parallel to the grain provides the lowest cutting force values (Costes *et al.* 2004) with chip formation characteristic of the Franz type 1 chip. Furthermore cutting at angles with the annual growth rings produces smaller cutting forces and less distorted grain compared to cutting against the growth rings (Goli *et al.* 2009).

Analysis of the formation of the surface finish also has been investigated (Goli *et al.* 2001a,b, 2002a; Goli and Uzielli 2004). Surface roughness measurements using a perthometer (optical 3D roughness measurement) and a profileometer (surface roughness stylus) were taken to quantify the surface finish of the woods. Machining in the standard machine directions (90°-0°, 0°-90°, 90°-90°) provides results concurrent to the respective chip formation types of Franz, McKenzie, and Koch.

Typically cutting along the grain provides a better surface finish than cutting across the grain, where the effects of moisture content, rake angle, depth of cut, and edge sharpness all affect the surface finish in the same way as previously investigated in the fundamental studies (Franz 1958; Koch 1964; McKenzie 1961). In reflection, when cutting at angles with and against the annual growth rings it is established that the surface

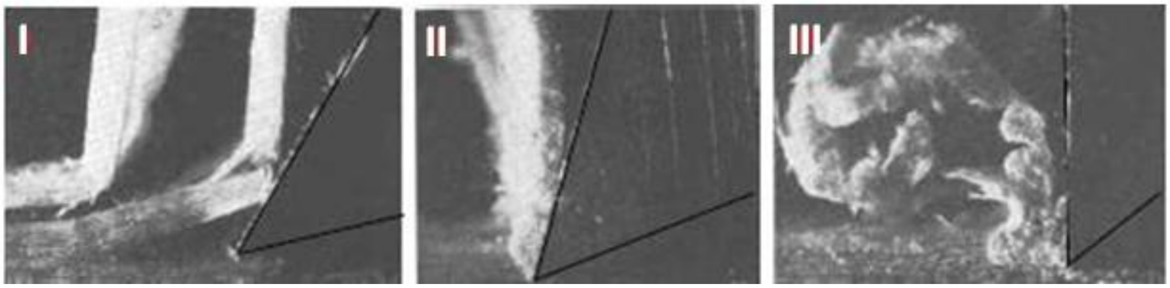

Fig. 2. McKenzie chip types, along the grain (McKenzie 1961) with permission from the University of Michigan

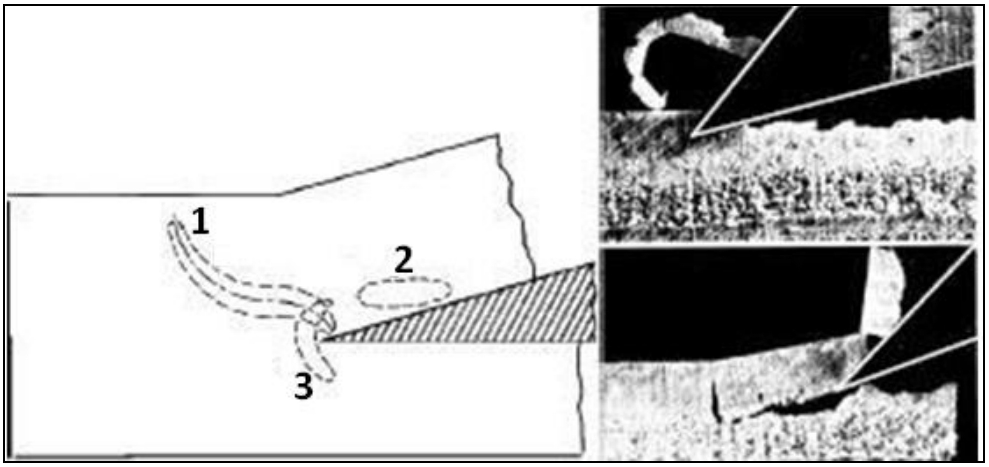

Fig. 3. Veneer Peeling, Across the Grain (Woodson and Koch, 1970) with permission from the U.S Department of Agriculture

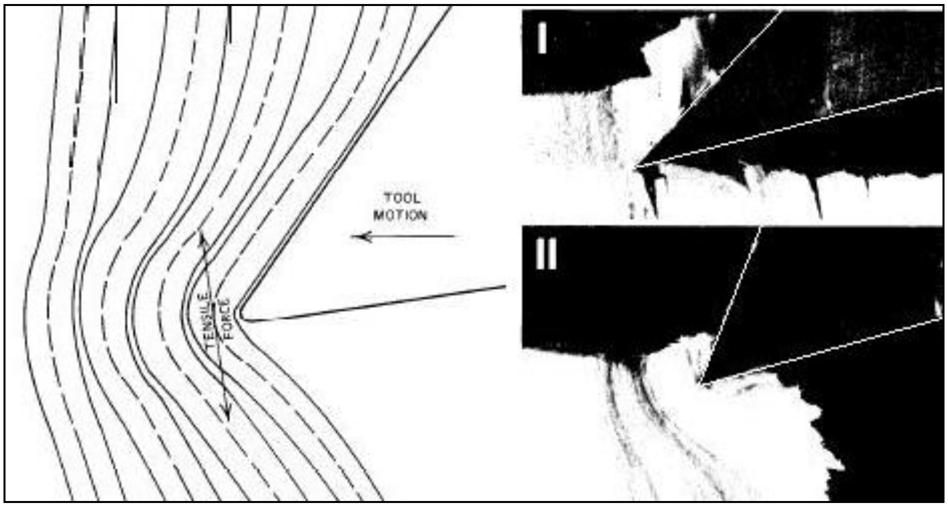

Fig. 4. Machining the wood end grain (Woodson and Koch 1970) with permission from the U.S Department of Agriculture

roughness is significantly larger when cutting at angles against the growth rings as opposed to with the growth rings. This has been verified by both surface roughness measurement techniques.

Oblique Plaining

In orthogonal cutting, it has been known for tools with large rake angles (>25°) to produce negative thrust forces (acting in a positive vertical direction relative to the work-piece), although this observation is usually attributed to a larger depth of cut (Franz 1958; Woodson and Koch 1970). For oblique cutting parallel to the grain, the cutting and thrust forces decrease as the oblique edge angle increases (Jin and Cai 1996, 1997). As observed with orthogonal cutting, it is also recognized that negative thrust forces can also occur when wood is machined using oblique tools (Jin and Cai 1997). This occurs for the same cutting conditions as with oblique cutting (large rake angles and depths of cut) for oblique edge angles over 30°. It is recognized that the negative thrust forces cause the propagation of longitudinal cracks in front of the knife edge during cutting (Franz 1958; Stewart 1971, 1986). By decreasing the rake angle and depth of cut, the magnitude of the negative thrust force becomes lower and eventually changes from negative to positive. This reduces the roughness of the surface caused by the chip splitting ahead of the tool, instead leaving behind a slight fuzzy grain (Fernando 2007).

It has been observed that fibers have been pulled out or up-rooted from the work-piece when cutting perpendicular to the grain (de Moura and Herandez, 2006). After further investigation, this phenomenon has been explained as being caused by lateral forces exerted on the work-piece by the oblique tool (de Moura 2006). This causes greater observed surface roughness when compared to that of surfaces that have been machined using orthogonal tools. Furthermore, an increase in the oblique edge angle causes more fibers to be pulled out, and hence, an increase in the surface roughness of the work-piece.

A study investigating cutting with extreme oblique angles (Fischer *et al.* 2011) states that cutting with very large oblique angles (45° to normal and above) provides a much better surface finish when compared with orthogonal cutting. This is a result of the time delayed edge engagement and an increased cutting edge contact with the work-piece. This effect also results in lower forces acting on the tool, which in turn, reduces tool wear.

TOOL WEAR

Causes of Tool Wear

In a comprehensive review on wood cutting tool wear (Klamecki 1979), it was concluded that the abrasive wear plays the largest role in the edge recession of tools. From recent studies (Bailey *et al.* 1983; Bayoumi *et al.* 1983, 1985; Mohan and Klamecki 1982; Scholl and Clayton 1987) it is evident that cemented carbide tools are extremely sensitive to corrosive wear, suggesting that high speed steel is a better corrosion resistant alternative. Having said this, corrosive wear has been known to significantly affect high speed steel when cutting green wood (McKenzie and Hillis 1965; Mohan and Klamecki 1982). This is due to much higher moisture content values as well as naturally occurring acids and phenolic compounds.

The presence of silica and other mineral entrapments is known to play a role in corrosive wear (Müller *et al.* 2011); however, further study has shown that the silica residue found within the wood cell walls plays a very small role. Instead, contamination with coarse silica during the harvesting and storage of timber/lumber is seen to contribute in a larger way to corrosion. It is also suggested that the mechanical properties of tool material at the tip, or even coating materials, can be altered by corrosive wear (Gauvent *et al.* 2006). This can allow the effects of abrasive wear to become more prominent or even result in brittle failure.

Effects of Tool Wear on Cutting Mechanics

Kivimaa was the first to notice an increase in cutting forces due to the dulling of the cutting edge (Kivimaa 1950). It has been documented that all of the tool forces (cutting, thrust, and side force) are sensitive to tool wear (McKenzie and Crowling 1969) with side force said to be the most affected by wear.

Further research documents a rise in the cutting force with respect to continuous length of cut (Pahlitzsch and Jostmeier 1965). Cutting force *vs*. length of cut has a similar trend to edge recession *vs*. length of cut (Bartz and Breier 1969); both exhibit a rapid exponential rise which then levels off. A more detailed study offers an explanation of how tool forces increase due to wear (Bier and Hanicke 1963), describing the wear and cutting force increase over a continuous length of cut in three stages:

1. An exponential increase in cutting force which plateaus. This is caused by the initial blunting of the tool.
2. A linear increase with small gradient. The tool is now blunt and this trend is caused by edge rounding where the radius gradually increases.
3. An exponential increase and then failure. When critical edge radius has been reached, the clearance face starts to wear, eventually causing the failure of the tooth.

Using this knowledge, research into a predictive model for tool wear was conducted (McKenzie and Cowling 1971), revealing a linear relationship between the main cutting force and the square root of the edge radius. It was also noted that the relationship between the main cutting force and wear on the clearance face was approximately linear.

When compared to the machining of wood using sharp tools, it is widely accepted that worn edges generally lead to a more compressed chip formation and to a work-piece with a fuzzier, protruded grain (Franz 1958; Kivimaa 1950; Koch 1964; McKenzie 1961; Woodson and Koch, 1970). This is true for all of the major machining directions.

MECHANICS OF WOOD SAWING

Tooth and Blade Geometry

Nomenclature for tooth geometry is detailed by British Standards (British-Standards-Institute 1999). The geometry of the saw teeth can be varied to suit the end use of the saw. Rip saws have unbeveled cutting edges and small rake angles to remove material parallel to the grain. Cross cutting saws, however, need negative rake angles and sharp beveled edges to sever the wood fibers perpendicular to the grain. Compound saw teeth have more than one cutting edge so that they can generally perform well cutting both parallel and perpendicular to the grain. Fleam teeth are usually seen on bow-saws for cutting green wood, where the rake and flank angles are the same to allow cutting in both directions.

The thicknesses for the blade raw material is also specified (British Standards Institute 1999) with the prospective user in mind. The teeth should be alternately set on either side of the blade. Approximately two-thirds of each tooth measured from the tip shall be set, and the method of setting shall be such that the remainder of the tooth will remain undeformed. The set width of the left and right set teeth should be equal and shall be expressed as a ratio of the thickness of the blade. For cross cutting and general use saws, this should be no less than one-fifth and no more than two-fifths the thickness of the blade on each side of the tooth. For rip saws no less than one-quarter and no more than one-half the thickness of the blade should be on each side. Saw blades use a variety of different set patterns depending upon the wood grain direction and the driving method (either manual or machine driven). Hands saws use a variation of the raker set.

During rip sawing, the wood fibers are initially compressed and then sheared (Lundstrum 1985). Post shearing the compressed fibers adjacent to the shearing edge causes them to spring back nearly to their original position. For this reason, the set of the saw must be large enough to prevent the sprung back fibers from making contact with the body of the saw. Softwoods produce fuzzy grain leaving the kerf not as cleanly cut as hardwoods, hence sawmills processing mainly softwoods apply greater set widths to the saw teeth.

Increased gullet size limits the number of teeth per unit of length of blade (*i.e.* decreases pitch). The feed velocity during sawing must be reduced for decreased pitch saws to prevent an excessive depth of cut per tooth, known as over-biting. Conversely, small gullet sizes tend to increase the tooth pitch (Lundstrum 1985). In band sawing, the cutting velocity needs to be reduced, as sawdust can become compressed within the reduced gullet. The reciprocating cutting stroke does not provide enough of a respite for the sawdust to be removed from the kerf. In order to overcome these problems, it is recommended that the area of the gullet should be approximately the same as the area of the tooth. Furthermore, the bite of the tooth should be approximately one third of set width. This is to ensure that the smallest of the sawdust particles will not be any larger than the set width and hence will be completely swept out of the machined groove by the set teeth, whereby reducing lateral cutting forces.

Using a blade with uniform tooth pitch results in the set and unset teeth having the same bite profile, and hence, the same principle cutting and thrust forces (Andersson *et al.* 2001). Using a differential pitch (*i.e.* the gullet size of the set teeth is smaller than that of the neutral teeth) means that the set teeth have only a fraction of the bite of the neutral teeth. This results in the role of the set teeth to be that of removing swarf from the kerf rather than actually performing any of the cutting action. Reduced lateral cutting forces and wear are observed for the set teeth.

Beveling the outer lateral edge of the set teeth reduces the bite profile and improves the surface quality through less damage to the fibers (creating cleaner cuts) (McKenzie 2000). Beveling the inner lateral edge of the set teeth can increase the bite profile up to two fold. This in turn can cause an increase in the cutting forces and a reduction in observed surface quality. Overall, beveled teeth reduce the cutting forces, hence improving cutting performance. Uniform tooth pitch and geometry results in high surface quality and accurate sawn dimensions. The number of teeth/points per 25 mm shall be in accordance to British Standards (British Standards Institute 1999).

Tool Forces

Cutting forces for single saw tooth tests are generally measured and recorded using one or more piezoelectric transducers. A piezoelectric transducer is a quartz crystal that generates an electric charge in response to an applied load. They can be calibrated to measure exact forces with very small margins of error. The simplest of data acquisition systems consist of a single transducer connected to a single saw tooth, aligned to measure the force in the direction of cutting (Ratnasingam and Scholz 2011). Where three transducers are simultaneously used to measure forces in the X, Y, and Z directions, they are collectively referred to as a force dynamometer. Dynamometers are generally set up to constrain the work-piece (wood), and thus, record the resultant forces applied by the single tooth. The transducers aligned in the X, Y, and Z directions are set up to record cutting, lateral, and thrust forces. Usually the X and Y directions record cutting or later forces and the Z direction records the thrust force, although this is completely dependent on orientation of the tool path with respect to the work-piece. This method has also been used for a constrained tooth with the work-piece attached to a moving feed bed (Loehnertz and Cooz 1998). Regarding wood cutting mechanics, the tool forces are the most important measured response attributed to the tooth for a repeatable work-piece (*i.e.* if the work-piece stays the same but the tooth changes). This can either be in the pure, unaltered force form (Axelsson 1994; Axelsson *et al.* 1993; Cristóvão *et al.* 2011; Ekevad and Marklund, 2011; Lhate *et al.* 2011; Porankiewicz *et al.* 2011), or as a specific force value with respect to depth of cut or volume of material removed (Cooz and Meyer 2006; Ko and Kim 1999; Orlowski *et al.* 2011; Orlowski and Palubicki 2009).

For band-sawing operations, machining across the wood fiber direction positive rake angles of 15°-30° are used for high power driven processes (Lundstrum 1985). The tooth is allowed to “hook” or “barb” onto the work-piece to allow for quick machining. These rake angles would be far too large for hand sawing operations, as the forces required for cutting would be too large to perform manually. Clearance angles are varied (between 6° and 16°) for varying feed velocities. This is to prevent the flank of the tooth from making unnecessary contact with the work-piece during sawing. This will decrease the overall friction hence reducing thrust forces. Research into the effects of changing the rake angle of band-saw teeth when machining the wood end grain (the 90°-90° direction), has yielded interesting results with regard to the force in the direction of cutting (Vazquez-Cooz and Meyer 2006). 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.

A comparison of the performance between individually set teeth and swaged teeth show a reduction in lateral forces for the swaged teeth (Okai *et al.* 2006). Furthermore a quadratic relationship has been established between the variation (standard deviation) of lateral forces and side clearance. Through analysis of the cutting and thrust and side forces, a mechanistic cutting force model could be developed evaluating the individual roles of the set and neutral teeth (Ko and Kim 1999). It was found that the unset teeth contribute to the majority of the cutting and thrust force, and the set teeth cause the majority of the lateral forces measured.

Regression analysis has been frequently used to develop predictive cutting force models for simple rip tooth geometries (Axelsson *et al.* 1993; Cristóvão *et al.* 2011;

Lhate *et al.* 2011; Porankiewicz *et al.* 2011) where a linear decrease in the cutting force for an increased positive rake angle (10° to 30°) has been observed (Axelsson *et al.* 1993). At the same time a linear increase in cutting forces is observed for increased edge radii (5 to 20 μm). This shows that in the ripping scenario, sharp teeth with small rake angles provide the lowest cutting forces. Factors that are considered to have a significant effect on the major cutting force are depth of cut, rake angle, and edge radius. Cutting force increases with depth of cut, increases with edge radius, and decreases with rake angle. Furthermore, cutting the wood end grain yields the largest cutting forces with the lowest cutting forces observed machining along the fiber direction. Work-piece parameters have been used as predictors in statistical modeling to describe force trends. The most often used parameters are density, moisture content, and grain direction. In addition to this, numerical coefficients have previously been determined to discretely quantify wood species (Porankiewicz *et al.* 2011). Adding additional moisture to a piece of timber leads to swelling; likewise, removing moisture from timber leads to shrinkage. As a result of this change in volume, the density did not dramatically change with respect to moisture content. Higher tool forces are observed when cutting wood species of greater density (Cristóvão *et al.* 2011; Lhate *et al.* 2011). It is generally accepted that tool forces decrease with increased work-piece moisture content, although an exception to this rule has been found for frozen wood specimen (Porankiewicz *et al.* 2011). Increased moisture content for frozen wood leads to an increase in tool forces. Furthermore, work-pieces at decreasing sub-zero temperatures lead to a significantly higher tool forces.

An investigation into lateral tool forces was conducted for sharp beveled tooth geometries (Ekevad and Marklund 2011). Very sharp teeth yielded insignificant lateral forces in all machining directions. Lateral forces only became noticeable when the teeth became worn or damaged. In this instance, high lateral forces were observed machining both the wood end grain (90°-90° direction) and the across the fiber direction (0°-90° direction), with lower lateral forces machining along the grain (90°-0° direction).

Evidence from fundamental literature suggests that cutting velocity has negligible effect on the forces acting on the tool. This is for the ranges of 0.2 m/s to 6.3 m/s along the grain (McKenzie 1961) and 2.5 m/s to 50 m/s across the grain (Kivimaa 1950).

Chip and Surface Formation

Research into the effects of varied rake angle band-saw teeth on the on surface formation was conducted (Vazquez-Cooz and Meyer, 2006). This was performed machining in the 90°-90° direction (wood end grain). Three teeth with 25°, 30°, and 35° rake angles were examined. 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 comparably lower rake angle of the tooth.

A high speed camera has been previously utilized 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 were 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 was for green wood, with the dry and frozen work-pieces yielded smaller broken wood particles. 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, which impedes removal of the material from the kerf.

CONCLUSIONS

1. The fundamental mechanics of wood machining have been well established through the published literature. These are illustrated here by the Franz, McKenzie, Woodson, and Koch chip formation types.

2. The primary mode of tool wear is abrasion. The worn tools cause excessive compaction of fibers during cutting, resulting in a fuzzy chip and respective poor surface finish to the work-piece.

3. Recorded tool forces and observed chip formation are the most common methods of evaluating the cutting mechanics of saw-teeth. Predictive force models have been developed using both tooth geometry parameters and work-piece (wood) properties.

4. The original findings from previous research have been identified. This will allow for further research to be conducted in the field of wood-sawing in order to investigate novel, previously unexplored areas. This includes (but is not limited to) the influence of geometric parameters associated with the saw-tooth on tool forces.

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Article submitted: February 15, 2013; Peer review completed: March 25, 2013; Revised version received and accepted: April 5, 2013; Published: April 9, 2013.