Evaluating the Cutting Mechanics of Woodworking Hand-Saw Teeth

Andrew Naylor

Abstract—**The research detailed in this paper investigates the chip formation modes for woodworking handsaw teeth. Two tooth geometries (beveled and un-beveled) were evaluated using a single tooth rig. A high speed video camera was used to observe the chip formation in real time. For both tooth geometries the video footage provides evidence of a shearing mechanism cutting along the wood grain, and a bending mechanism cutting across the wood grain. Un-beveled teeth (with orthogonal edges) generally yield high cutting forces yet are very effective at removing material along the wood grain in a "chisel like" cutting action. Beveled teeth with sharp lateral edges generally yield low cutting forces and are well suited to severing the wood fibers perpendicular to the grain in a "knife like" cutting action.**

Index Terms—**Wood sawing, high speed photography, cutting mechanics.**

I. Introduction

Traditionally there are two types of tooth geometry for wood-cutting handsaws: The first type can be described as un-beveled (rip) teeth. These are widely understood to act as orthogonal cutting tools and are used by carpenters to remove material along the wood grain in a "chisel" like action. The second type can be described as beveled (cross-cutting) teeth. These are employed to sever wood fibers perpendicular to the grain. This paper takes these two common assumptions at face value and further investigates the precise mechanics of cutting.

A comprehensive review into wood machining (focusing on sawing) has been conducted by this author [1]. This supports the hypothesis that, in general, there are three types of factors that have a significant influence on the cutting mechanics:

1) Factors attributed to the machining process
2) The bulk properties of the wood
3) The moisture content of the wood

Analysis of the wood cutting process in some of the earliest studies [2]-[5] examines all of these three groups in detail. The most fundamental studies conducted by Franz [2], McKenzie [3], Woodson and Koch [4] provide adequate respective models for wood machining using simple, orthogonal tools.

Excluding studies carried out by this author [6], [7], the small amount of research that focuses on saw-teeth does not adequately consider wood as a heterogeneous material [8]-[16]. Quite often only density and moisture content are considered when developing predictive tool force models. In short, different mechanical properties in multiple directions need to be obtained to credit the isotropic, heterogeneous nature of wood.

II. Findings from Previous Study

Two numerical models have previously been developed by this author to predict the force in the major direction of cutting both along and across the wood grain [6]. Mechanical properties using standard test procedures [17] were obtained and used as categorical predictors.

The cutting tests were performed in a controlled experimental rig machining both along and across the wood grain (Fig. 1). Only an un-beveled tooth was used to perform the cutting action. This was done to maintain focus on the work-piece properties rather than the tooth geometry. When the saw-tooth passed through the work-piece, the calibrated dynamometer registered charge signals in the X, Y and Z directions. These signals were then amplified, processed via a PLC and then logged on the computer using LabView. The signals in the Y and Z axes (side and thrust force respectively) were minimal and hence not carried forward for further analysis.

Each predictive model demonstrated a strong correlation between the cutting force and specific mechanical properties: The cutting force along the grain correlated well with shear strength (τ) and toughness (Us). The cutting force across the grain correlated well with bending strength (M.O.R) and toughness (Ub). In both instances elastic moduli (G and M.O.E) were poor predictors. Density (ρ) however did act as a reasonably good predictor in both directions. To the best knowledge of this author, this is the first time that specific mechanical properties have been used to create predictive tool force models along and across the grain respectively.

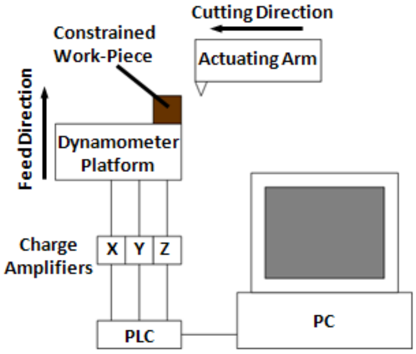

Fig. 1. Test rig schematic diagram.

Manuscript received October 23, 2013; revised January 20, 2014.

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DOI: 10.7763/IJMMM.2014.V2.111

III. High Speed Video Methodology

To reiterate, the novel aspects of this study is the observation of the chip formation using high speed photography. A high speed video camera was acquired to record footage at the tool work-piece interface. The camera was set up to record 1000 frames per second using a macro lens to capture chip formation at the macroscopic level. The cutting mechanics of two different types of saw-tooth were evaluated using this method:

1) An un-bevelled (rip) tooth with an orthogonal cutting edge. This tooth has a negative rake angle (γ) of 13º and a flank angle (α) of 51º (Fig. 2).
2) A tooth with a bevelled rake and flank faces of 28 º. This tooth has a negative rake angle of 15 ºand a flank angle of 48 º(Fig. 3).

When recording the chip formation of a **group** of teeth the camera lens had to be tilted at a downward angle allowing it to view the longitudinal work-piece plane. Unlike the tool forces experiment, the interaction between the tooth and the work-piece had to be visible at all times. This meant that a group of teeth could not be passed through the work-piece before the single tooth. This difficulty was resolved by using a small inclined group of four unset teeth.

The first tooth would perform little to no cutting action before each of the following three subsequent teeth passed through the work-piece. This allowed for a constant depth per tooth visible to the high speed camera. A 0.15 mm depth of cut was achieved by inclining the teeth by 3 ° (based on a uniform tooth pitch of 7 teeth per 25 mm). 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.

IV. Chip Formation Results

Freeze frame analysis of the high speed video footage across the grain provided a dynamic representation of the wood fibers deformation in bending initiated by the un-beveled tooth geometry (Fig. 4). Freeze frame analysis along the grain shows continuous chip formation (Fig. 5). Each chip is formed normal to the orthogonal cutting edge and hence is transported into the gulled and removed from the kerf. This explained why this type of tooth geometry is so often used along the grain. The chiseling action of the orthogonal edge and the role of the gullet ensure an efficient removal of material along the wood grain.

Analysis of the high speed footage for the beveled tooth geometries also exhibits continuous chip formation implying a shear failure mode (Fig. 6). The only difference between the beveled and un-beveled teeth is the direction of the chip formation. Freeze frame analysis shows the chips formed normal to the beveled rake face, which itself is at a tangent of 28 ° to the cutting direction. The fact that the gullet plays no significant role suggests that the gullet does not efficiently transport and remove the chip from the kerf. This explains why beveled teeth are not often employed to machine along the wood grain. Freeze frame analysis and microscope images of the beveled teeth exhibit less deformation due to bending across the grain when compared to the same analysis for the un-beveled teeth (Fig. 7). The wood fibers appear significantly less deformed and the kerf width is visibly narrower. It is known from related research [7] that there is much less of an interaction between the tooth cutting area and the work-piece for beveled tooth geometries. This lower contact area maintained during cutting results in the narrower kerf width.

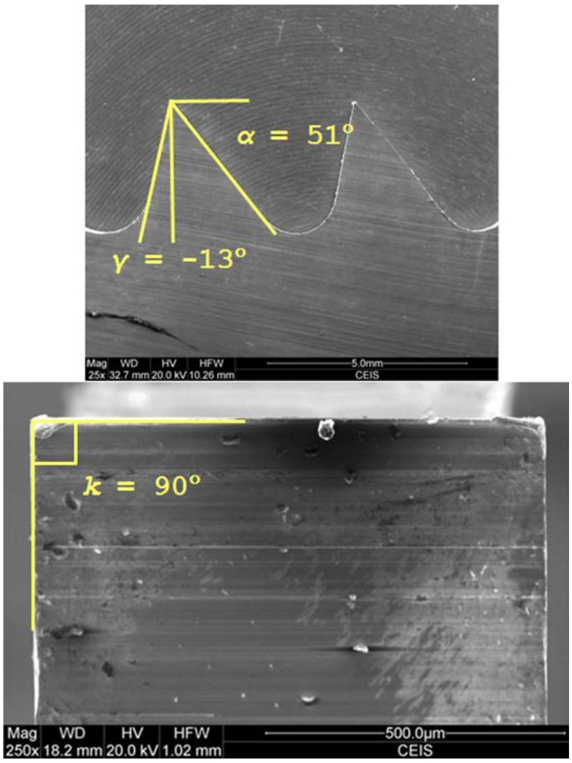

Fig. 2. Un-beveled tooth SEM measurement.

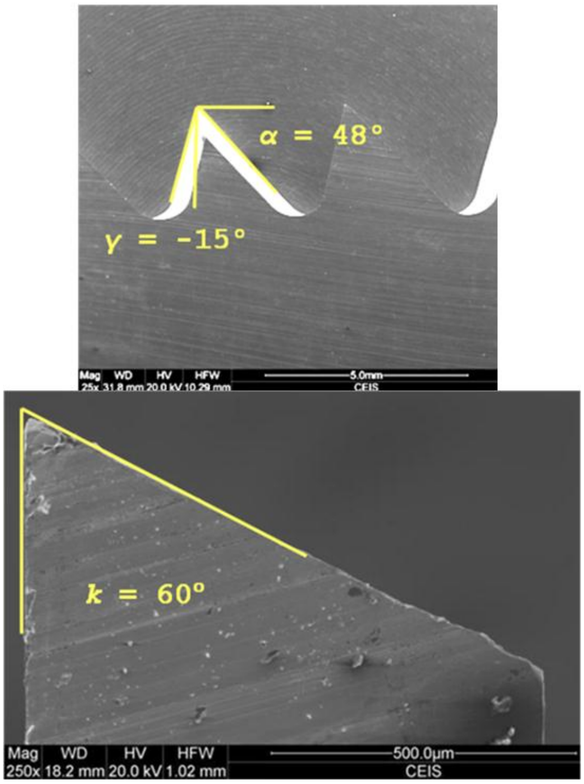

Fig. 3. Beveled tooth SEM measurement.

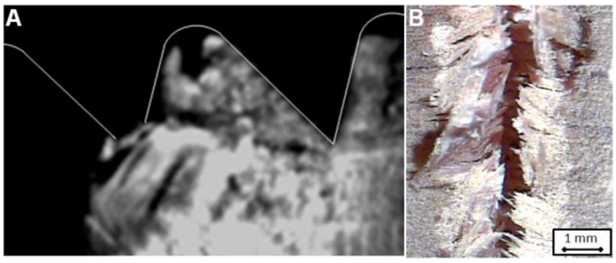

Fig. 4. Un-beveled across the grain

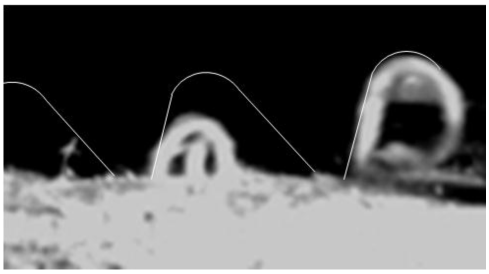

Fig. 5. Un-beveled along the grain.

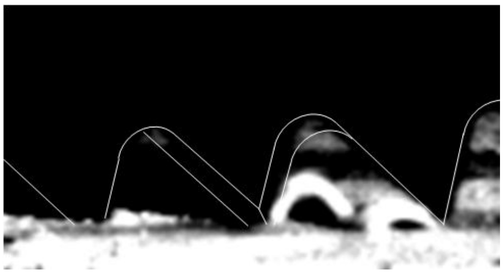

Fig. 6. Beveled along the grain.

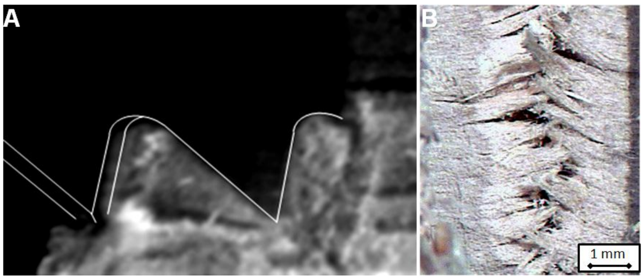

Fig. 7. Beveled across the grain.

V. Discussion

Cutting along the grain with un-bevelled (orthogonal) teeth can be described as a shearing process. This has been proven both visually through high speed footage/microscope images and numerically through the statistically valid numerical models. Cutting along the grain with bevelled tooth geometries can also be described as a shearing process. The chip formation is continuous (similar to un-bevelled teeth) the only difference is that the chip is formed at a tangent of 28 ºto the tool path. The un-bevelled geometry produces chip formation in the direction of the tool path. This forces the chip into the gullet hence efficiently removes material from the kerf. The bevelled tooth geometries do not effectively remove material from the kerf.

Cutting across the grain with un-bevelled (orthogonal) teeth can be described as a bending process. Once again this has been proven both visually through high speed footage / microscope images and numerically through the predictive cutting force models. The surface formation across the grain for the bevelled tooth reveals a visibly narrower kerf when compared to the un-bevelled tooth. This is because throughout the cutting process a smaller tooth contact area is maintained with the work-piece.

VI. Conclusion

The chip formation types detailed in this study support the findings of the previously published numerical models [6]. This provides very strong evidence that the cutting mechanism across the grain, for both beveled and un-beveled teeth, can be described as a bending mode. The cutting mechanism along the grain can be described as a shear mode.

The cutting mechanics of the un-beveled tooth geometry along the grain can be compared to “chiseling”. The cutting mechanics of the beveled tooth geometry across the grain can be compared to “knife cutting”.

Acknowledgment

The author would like to acknowledge the support of the industrial collaborators SNA Europe - the manufacturers of BAHCO® handsaws.

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