Meulenberg *et al. Journal of Wood Science* (2022) 68:18
https://doi.org/10.1186/s10086-022-02023-8

Journal of Wood Science

ORIGINAL ARTICLE

Open Access

Minor cutting edge force contribution in wood bandsawing

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Abstract

As the sawmill industry is moving towards thinner bandsaws for higher yields, it is important to study the cutting force in more detail. The cutting force can be split into two zones. Zone I concerns the force on the major cutting edge as well as the friction force on the major first flank. Zone II considers the forces on the minor cutting edges as well as the friction forces on the minor first flanks. Zone II cutting can significantly affect the cutting force and has not been studied in great detail. Frozen, non-frozen and dry heartwood of Norway spruce and Scots pine were cut using different tooth geometries and the cutting force was measured. The major cutting edge, clearance, band thickness, minor cutting edge angle and minor cutting edge clearance angle were investigated. The y-intercept of the cutting force–width graph was used as the Zone II force (at this point the Zone I forces are assumed to be zero). The Zone II force contribution to the cutting force was studied. The results show that frozen wood has less elastic spring-back and therefore less Zone II cutting. Dried wood showed a significantly higher degree of Zone II cutting (55—75% contribution to the cutting force). Changing the major cutting edge from 2.87 mm to 1.6 mm resulted in 10–15% higher Zone II force contributions.

Keywords: Saw, Minor cutting edge, Norway spruce, Scots pine, Clearance angle, Minor first flank, Major cutting edge

Introduction

The Swedish sawmill industry has expressed an interest in the optimisation of bandsawing and the development of thinner cutting teeth. This allows for the production of a larger volume of timber while reducing the waste products such as sawdust and chips. The benefits are furthermore both economic and environmental as not only is waste reduced, but the volume of end products that can bind carbon dioxide for a longer time is increased. When developing more efficient bandsawing cutting tools, the cutting forces need to be considered with respect to the tooth geometry, such as the major cutting edge, clearance and cutting angles as these can increase the sawing yield and affect the cutting process [1–3].

The cutting geometry of a bandsaw tooth can be seen in Fig. 1 according to the ISO 3002:1 standards [4]. Note that the teeth are symmetrical in X-direction. The width of the major cutting edge (S_t) is a crucial geometrical feature of a saw tooth as it is responsible for the extent of material removal. Sawing teeth also have a clearance (u) (distance between the tooth tip (S_t) and the band (S): $2u = S_t - S$) which avoids contact between the back of the band and the wood as the cutting teeth create kerfs. The minor cutting edge angle, κ_r' (also called the radial clearance angle), as well as the uncut chip thickness, h_m, is largely responsible for the minor cutting edge geometry interacting with the wood (see Fig. 2). The combination of the minor cutting edge angle, κ_r', and minor cutting edge clearance angle, α_p' (also called the tangential clearance angle) determines the geometry of the minor first flanks, $A'_{\alpha 1}$ (also called the side faces).

Wood is an elastic material and therefore when it is cut, some of the fibres bend over instead of being broken.

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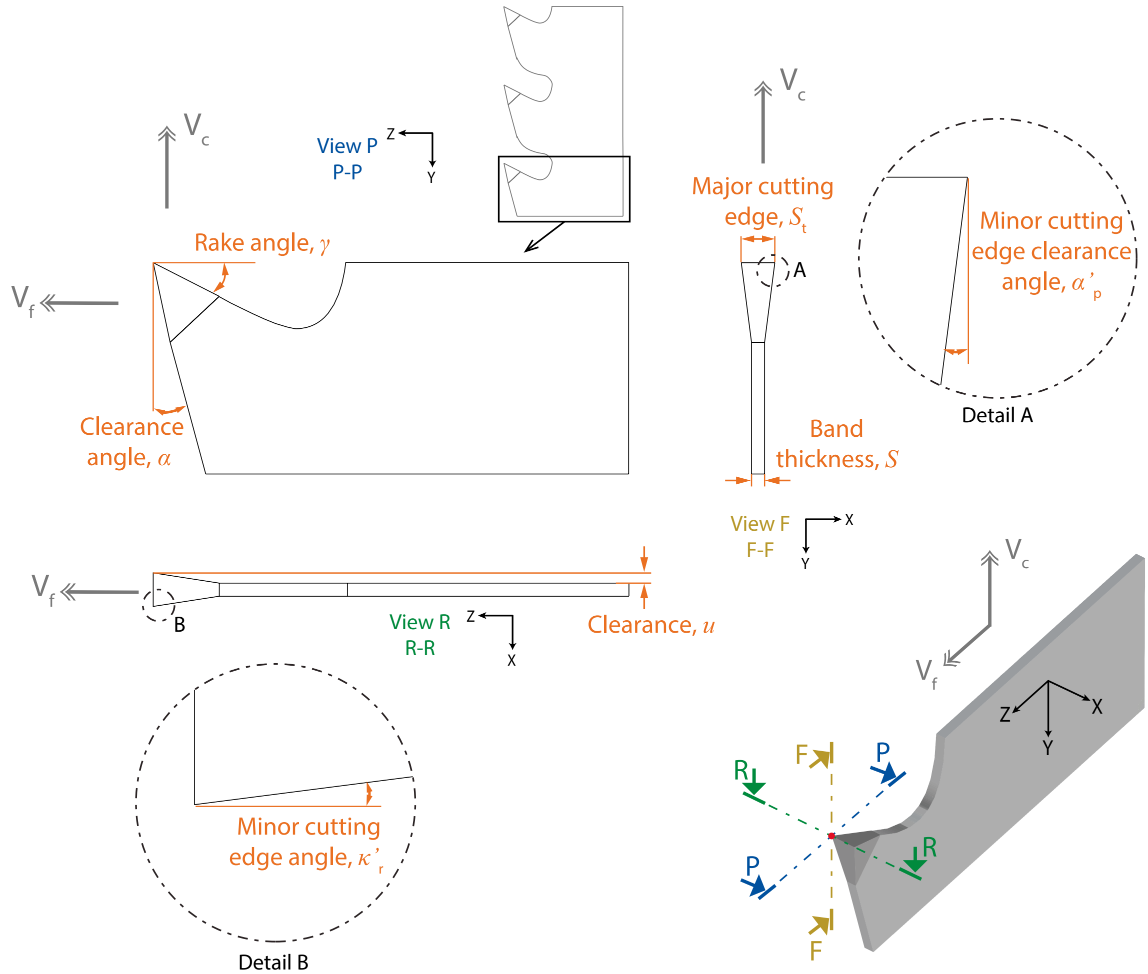

Fig. 1 Geometry of a single cutting tooth used in wood sawing according to ISO 3002:1 [4]

These fibres return to their original position after the cutting edges have passed which is known as elastic springback. The wood that has sprung back will make contact with the minor first flanks, $A'_{\alpha 1}$, and major first flank, $A_{\alpha 1}$ (also called the clearance face). The elastically sprungback wood will also lie in the cutting path of the consequent tooth, leading to an increase in friction.

The forces that act on sawing teeth are one of the factors that describe the overall cutting process. Others include the surface roughness of the workpiece, temperature, vibrations, etc. The conventional forces on a cutting tooth are defined by the cutting force (F_c), the feeding force (F_f), and the lateral force (F_p) (see Fig. 3). The cutting force (also called the main or parallel force) is responsible for material removal and is consequently the highest force. It acts on the tooth in the opposite direction of the bandsaw cutting movement, v_c, which is linear in bandsawing. This force occurs on the major cutting edge but also on the minor cutting edges, depending on the uncut chip thickness (h_m). The cutting force can be split into different components as shown in Eq. 1 [5]. This equation states that the cutting force can be split into the force acting on the major cutting edge (F_{cS}), the force acting on the two minor cutting edges ($F_{cS'}$) and the friction force between the two minor first flanks and the workpiece ($F_{cS'\mu}$):

$$F_c = F_{cS} + 2F_{cS'} + 2F_{cS'\mu} \quad (1)$$

Equation 1 can be modified to clearer distinguish between the different force components as show in Eq. 2. Here, the cutting force acting on the major cutting edge (S_t) is given by F_{cS}, and the friction force between the elastically sprung-back wood and the major first flank ($A_{\alpha 1}$) has been separated from F_{cS} and is given by $F_{cS\mu}$. This is indicated in the red Zone I in Fig. 4 and it represents the major cutting edge cutting. The cutting force on the minor cutting edges (S'_t) is given by $2F_{cS'}$ and the

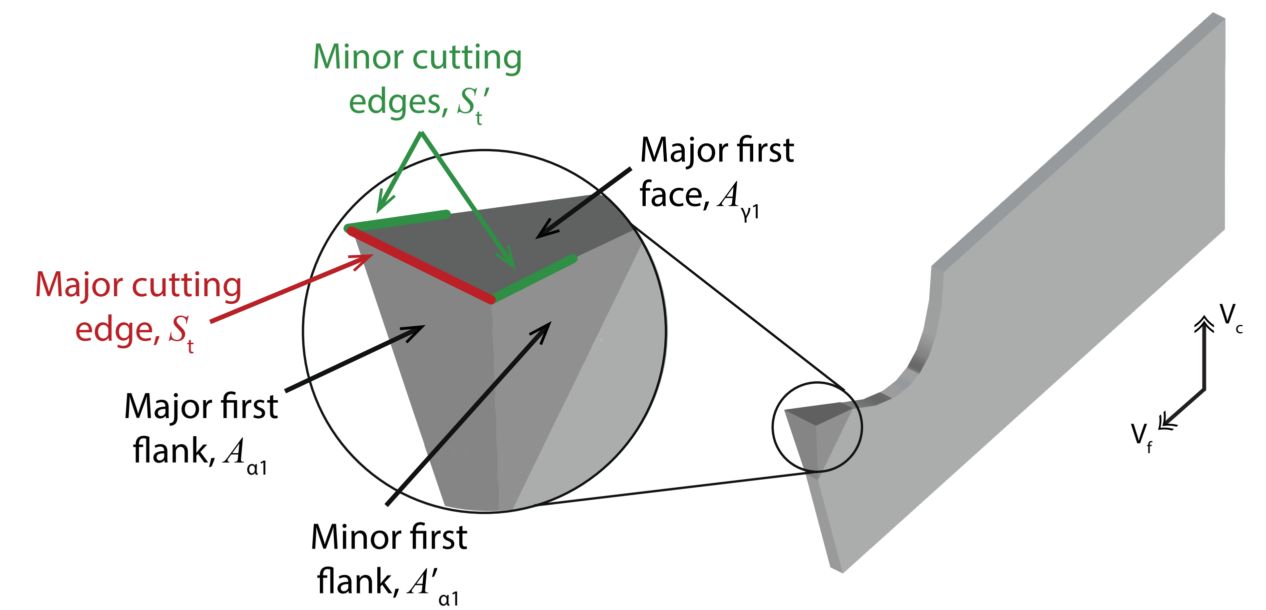

Fig. 2 Faces and cutting edges of a wood saw tooth according to ISO 3002:1 [4]

friction forces on the two minor first flanks ($A'_{\alpha 1}$) is given by $2F_{cS'\mu}$. These force components are indicated in the green Zone II of Fig. 4. To distinguish between major and minor cutting edge cutting, the equation has been split into two parts denoted by F_{I} and F_{II}, each representing a different zone in Fig. 4. This paper concerns the force contribution from Zone II and is defined by F_{II} in Eq. 4:

$$F_c = F_{cS} + F_{cS\mu} + 2F_{cS'} + 2F_{cS'\mu} \tag{2}$$

$$F_{\mathrm{I}} = F_{cS} + F_{cS\mu} \tag{3}$$

$$F_{\mathrm{II}} = 2F_{cS'} + 2F_{cS'\mu} \tag{4}$$

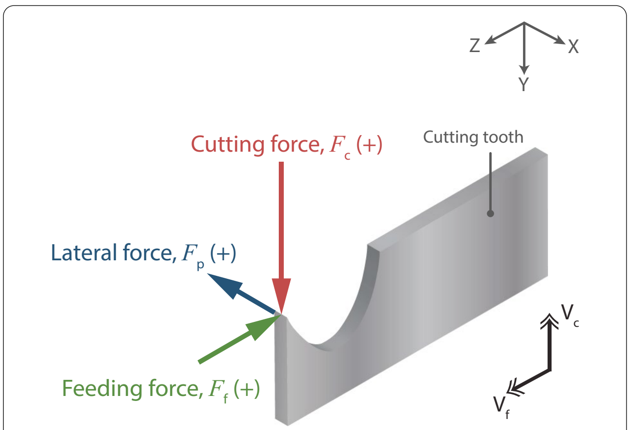

Fig. 3 The three principal forces acting on a saw tooth

$$F_c = F_{\mathrm{I}} + F_{\mathrm{II}} \tag{5}$$

When the major cutting edge is reduced, F_{I} is reduced, but the force contribution from Zone II, F_{II} remains constant and will therefore have a larger influence on the overall cutting force, F_c. The force contribution from the minor cutting edges and the friction force between the minor first flanks and the workpiece, Zone II, has scarcely been investigated in literature. As the industry is moving towards smaller major cutting edges, it is crucial to better understand the contribution of these forces to the cutting force, and to pay more attention to the minor edge geometry and minor first flank geometry. Furthermore, when the Zone II cutting increases, the wear behaviour of the cutting teeth as well as the temperature distribution in the tooth can change, which could lead to tooth failure and instabilities during sawing.

Cutting by the minor cutting edges occurs in a different direction than cutting by the major cutting edge. For example, when the major cutting edge is cutting in the 90°–90° direction, the minor cutting edges cut in the 90°–90° direction, or in a 2°–90° if the minor cutting edge angle is 2° (see Fig. 5). The first number in this notation indicates the cutting edge direction with respect to the fibre angle, whereas the second number indicates the movement direction with respect to the fibre angle [6]. The cutting direction can significantly affect the forces [3, 6–12]. Cutting by the minor first flanks of the tooth occurs at 0° to the fibre angle and the tooth is moving in a direction of 90° to the fibre angle, a cutting action similar

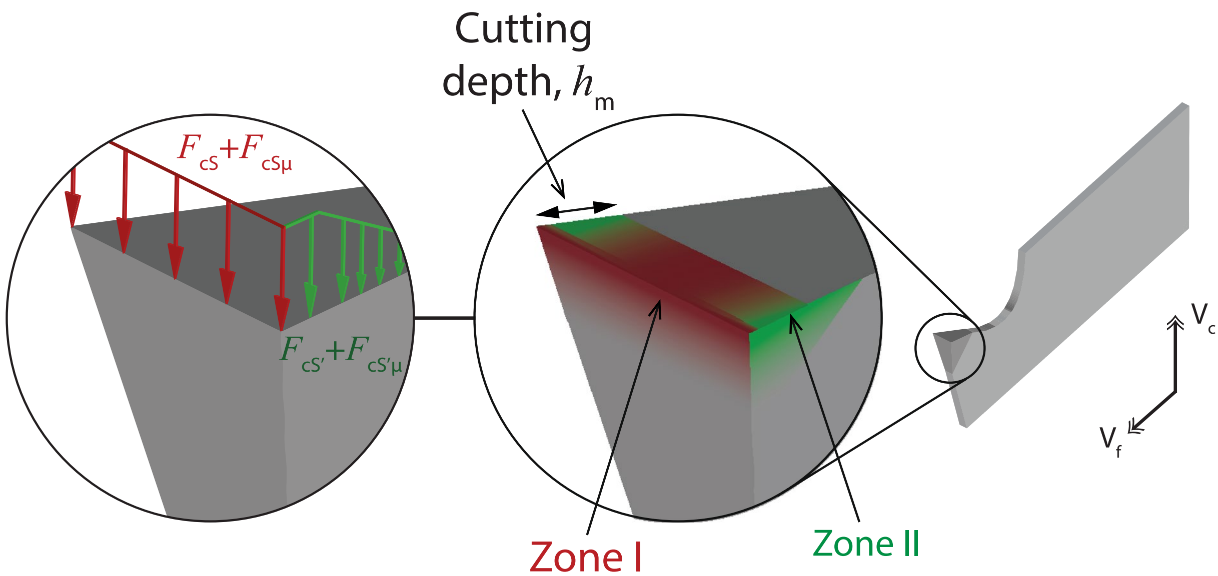

Fig. 4 The cutting force can be divided into two zones: Zone I major cutting edge force (F_{cS}) and friction forces on the major first flank ($F_{cS\mu}$) and Zone II minor cutting edge forces ($F_{cS'}$) and friction forces on the minor first flanks ($F_{cS'\mu}$)

to veneering. Cutting in this direction has significantly lower cutting forces [6, 13]. Li et al. [3] found that Zone II cutting contributes up to 7% to the cutting force in the 90°–90° direction, but they found that the Zone II force contribution can be as high as 16.9% in the 0°–90°, where Zone II cutting is occurring in the 90°–90° direction.

The Scandinavian species Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) are processed in all environmental conditions, even when temperatures drop well below zero. Sawmills, therefore, process frozen logs, non-frozen logs and dry wood. This study considered Norway spruce and Scots pine in frozen, non-frozen and dry condition. The Zone II force contribution was analysed while changing the major cutting edge as well as the clearance, minor cutting edge angle (κ_r') and minor cutting edge clearance angle (α_p'). To the author's knowledge, the minor cutting edge force

Table 1 Average density, moisture content and temperature of Norway spruce and Scots pine samples just before being cut

Species	Cutting condition	Density [kg/m^3]	Moisture content [%]	Temp. [°C]
Norway spruce	Non-frozen	450	72	20
	Frozen	450	72	− 20
	Dry	300	13	20
Scots pine	Non-frozen	480	44	20
	Frozen	480	44	− 20
	Dry	460	13	20

Table 2 Overview of cutting tooth geometries of series 1 where the clearance, band thickness and major cutting edge change

Feature	Symbol	Unit	Tooth no.								
			1	2	3	4	5	6	7	8	9
Major cutting edge	S_t	mm	2.87	***2.47***	***2.07***	***2.60***	***2.20***	***1.80***	***2.40***	***2.00***	***1.60***
Band thickness	S	mm	1.47	1.47	1.47	***1.20***	***1.20***	***1.20***	***1.0***	***1.0***	***1.0***
Clearance	u	mm	0.7	***0.5***	***0.3***	0.7	***0.5***	***0.3***	0.7	***0.5***	***0.3***
Minor cutting edge	S_t'	mm	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Rake angle	γ	deg	27	27	27	27	27	27	27	27	27
Clearance angle	α	deg	12	12	12	12	12	12	12	12	12
Minor cutting edge angle	κ_r'	deg	2	2	2	2	2	2	2	2	2
Minor cutting edge clearance angle	α_p'	deg	2	2	2	2	2	2	2	2	2

Bold-italic values indicate changed parameter values

Table 3 Overview of cutting tooth geometries of series 2 where the minor cutting edge angle and minor cutting edge clearance angle are changed

Feature	Symbol	Unit	Tooth no.			
			1	10	11	12
Major cutting edge	S_t	mm	2.87	2.87	2.87	2.87
Band thickness	S	mm	1.47	1.47	1.47	1.47
Clearance	u	mm	0.7	0.7	0.7	0.7
Minor cutting edge	S_t'	mm	0.9	0.9	0.9	0.9
Rake angle	γ	deg	27	27	27	27
Clearance angle	α	deg	12	12	12	12
Minor cutting edge angle	κ_r'	deg	2	***0***	***6***	2
Minor cutting edge clearance angle	α_p'	deg	2	2	2	***6***

Bold-italic values indicate changed parameter values

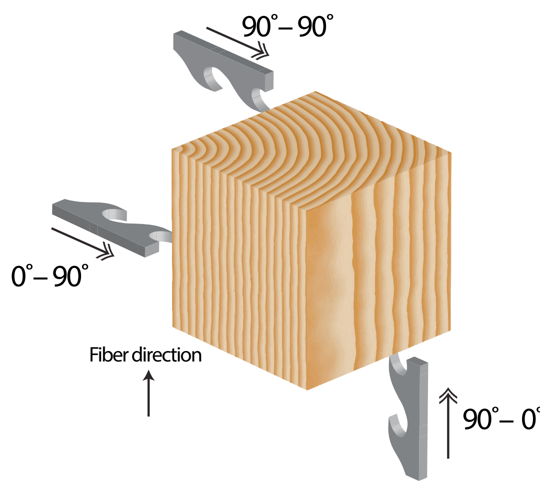

Fig. 5 Definition of cutting directions. Cutting force tests were made in the 90º–90º cutting direction, i.e. the cutting edge and the feeding direction were 90º to the longitudinal fibre direction of the wood

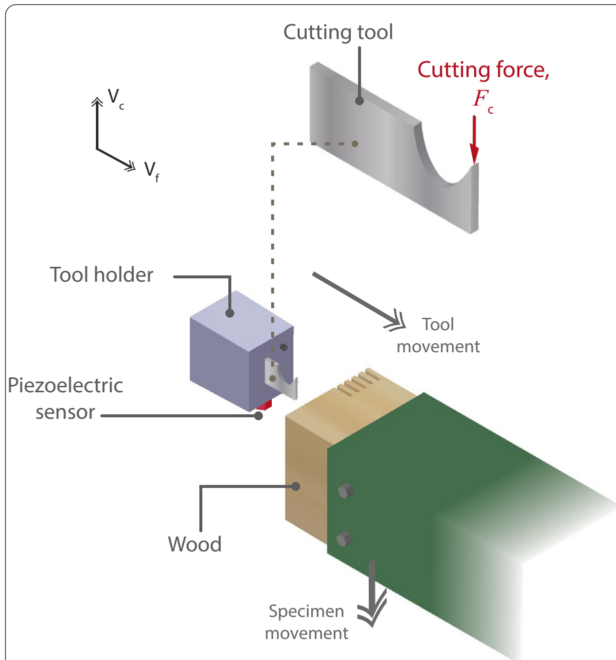

Fig. 6 The experimental setup shows how the wood piece moves while the tooth is moved into the wood by the tooth holder

contribution has not been reported in previous literature. Thus, this research can provide insight into the force behaviour on the minor cutting edges, especially as the industry is moving towards more efficient sawing with optimised cutting tools.

Materials and methods

Wood specimen

Logs of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) were harvested from the same forest in the north of Sweden during spring. Specimen of 70 × 70 × 200 mm were cut from the logs. The average specimen moisture contents (mass of water/mass of dry wood), density and temperature right before testing are indicated in Table 1. The density was measured using a CT (computed tomography) scanner and the samples were checked for defects such as knots in order to avoid them during cutting. All tests were done in the heartwood and the non-frozen and frozen samples were tested in green condition.

Cutting teeth

Stellite-tipped cutting teeth were cut out from a new industrial steel bandsaw blade. The geometry is defined in Figs. 1, 2. Two series of teeth were tested: for the first series, the clearance and band thickness were altered which had a direct effect on the major cutting edge ($S_t = S + 2u$) as can be seen emphasised in Table 2. For the second series, the minor cutting edge angles and minor cutting edge clearance angles were altered (see emphasised values in Table 3). Note that the minor cutting edge was determined from h_m and κ_r'. Tooth no. 1 is currently used in many Swedish sawmills, and was used as a reference in both series. The geometry was chosen based on a questionnaire from several Swedish sawmillers and tool producers to ensure that the parameters are realistic for practical manufacturing and use. The sharpness of each tooth was controlled by making very shallow cuts into a very hard species of African wood (Muanga, *Pericopsis angolensis*). This removed the initial sharp edge (with tip radii between 4 and 8 μm) and gave the cutting teeth a 'work-sharp' edge (radii between 10 and 15 μm) which they maintain for longer: approximately 8 h of cutting. It is crucial to remove the initial sharp edge as this can affect the forces significantly at the beginning of cutting.

Cutting force measurements

A custom-made cutting force machine first described by Axelsson et al. [7] was used to conduct tests in the 90°–90° cutting direction (Fig. 5). A 1-m arm held the wood specimen and rotated at a speed of 15 ms^{-1}. A cutting tooth was fed into the wood using a tooth holder controlled by a stepper motor. A piezoelectric sensor on the tooth holder measured the forces as the cutting kerfs were created; see Fig. 6. The signals were transformed to account for the distance between the tooth tip and the sensors. The uncut chip thickness, h_m, was 0.9 mm/cut, and ten cuts were made per kerf, which means that the total kerf depth was 9 mm. Ten kerfs were made per cutting tooth and 100 data points were collected per tooth. For a more detailed description of the data collection, please refer to Meulenberg et al. [14].

Elastic spring-back

The elastic spring-back of the different wood species and conditions was determined by measuring the kerf width directly after the cuts were made. First, the average width of each kerf was measured using a DSX1000 (Olympus) digital microscope. The elastic spring-back was then calculated with respect to each exact major cutting edge (also measured using the digital microscope) using Eq. 6. The measurements could not be done for dried wood since the kerf sides and surfaces were too damaged and ragged to accurately measure:

$$\text{Spring-back} = \frac{S_t - k}{S_t} \cdot 100\%, \tag{6}$$

where

k =kerf width.

Zone II force contribution

To determine the Zone II force contribution for the different species and wood conditions, the cutting force was plotted against the major cutting edge. A best-fit line of the data was created showing a clear linear relationship between the cutting force and major cutting edge. The equation of this line as well as the explained variance (R^2) was obtained. The y-intercept of the line of best-fit was taken as the Zone II force components ($F_{II} = 2F_{cS'} + 2F_{cS'\mu}$). At the y-intercept, the major cutting edge is zero and any remainder force can be

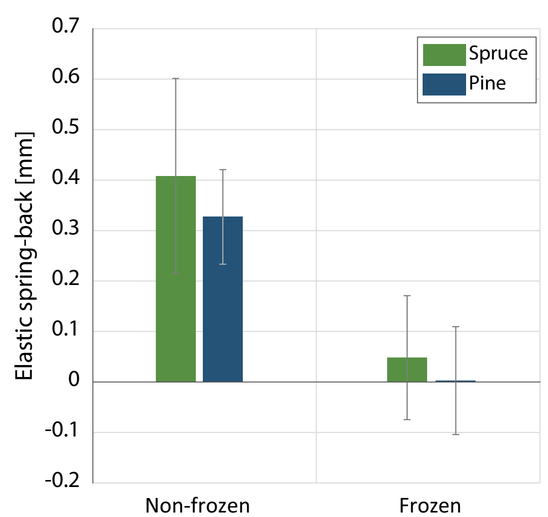

Fig. 7 Elastic spring-back of frozen and non-frozen Norway spruce and Scots pine

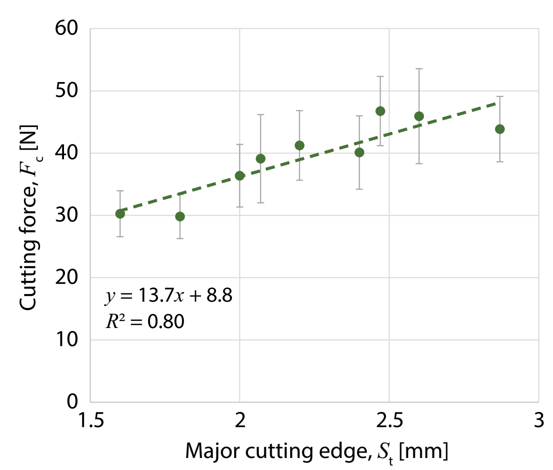

Fig. 8 Example of a force–width graph: a best-fit line indicates a y-intercept of 8.8 N for non-frozen Norway spruce (please note the lower limit of the x-axis). The y-intercept is an approximation of the Zone II forces (F_{II})

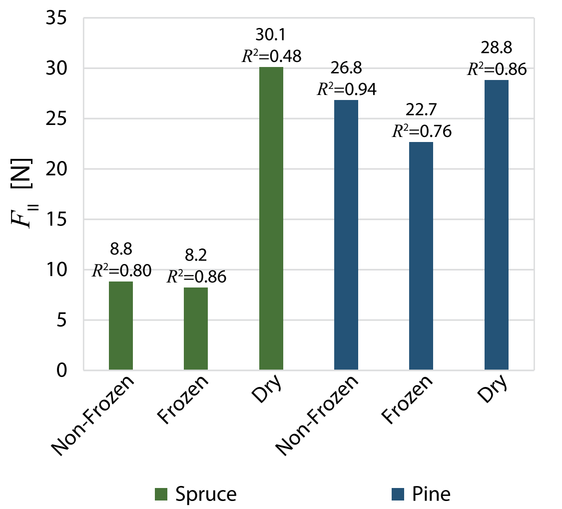

Fig. 9 The F_{II} estimates (y-intercepts in the force–width plots) of the different cutting conditions and species. The R^2 value is indicated on top of the bar as well as the exact force value

contributed to Zone II cutting. F_{II} was then divided by the cutting force (F_c) of each tooth (see Eq. 7), providing the Zone II force contribution to the cutting force. With this percentage, the cutting force could be described in two parts: (1) percentage of cutting done by the major cutting edge and (2) percentage of cutting done by the minor cutting edges. This ratio is based on the linear model fitted to the data points, and this model does not consider that there is a change in clearance:

$$\text{Zone II force contribution} = \frac{F_{II}}{F_c} \cdot 100\% \quad (7)$$

Results and discussion

Elastic spring-back

The elastic spring-back can be as high as 0.4 mm for non-frozen Norway spruce as can be seen in Fig. 7, which means that each minor first flank ($A'_{\alpha}1$) comes into contact with approximately 0.2 mm of wood. This is quite significant for wood sawing teeth as $\kappa'_r = 2°$ which leaves only 0.03 mm of space for elastic spring-back. This will result in a significant compressive force by the wood on the tooth minor first flanks, resulting in high friction forces. With such large spring-back quantities, the minor cutting edge and minor first flank makes up to 5.7 mm of contact with the wood. Frozen wood had significantly lower elastic spring-back due to a higher rigidity and Scots pine has less spring-back than Norway spruce due to higher mechanical properties such as the elastic modulus.

Series 1: major cutting edge, clearance and band thickness

The cutting force was plotted against the major cutting edge. In Fig. 8, an example of such a graph can be seen for non-frozen Norway spruce. The average values are given with circular markers along with the standard deviations. Note that a majority of the spread is assumed to be due to changes in the wood such as density variations along the growth rings. A linear best-fit line indicates the y-intercept which is a representation of the F_{II} contribution.

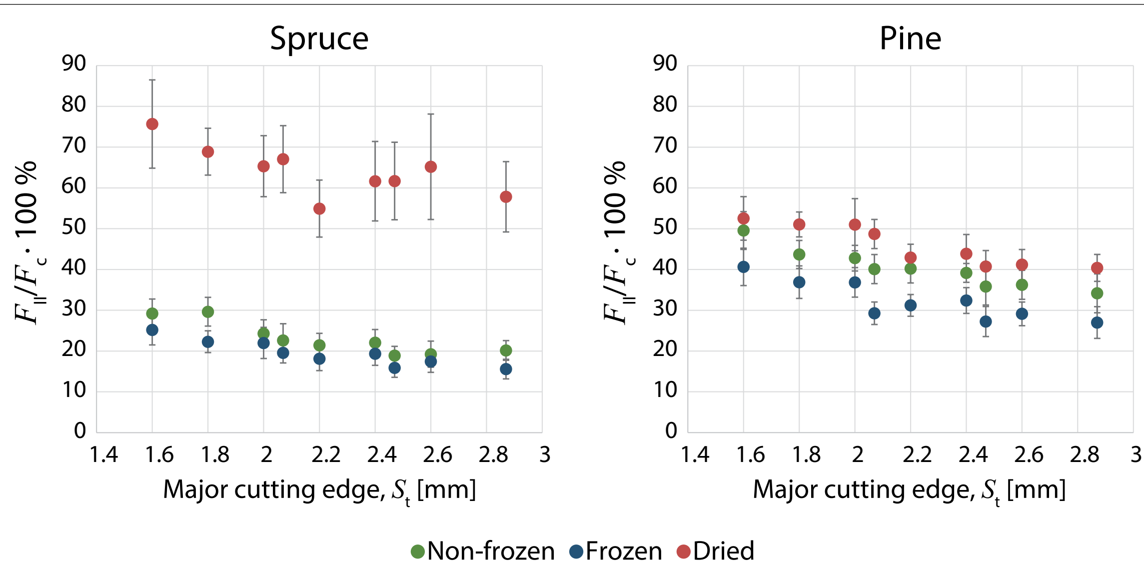

Fig. 10 The Zone II force contribution to the cutting force for different major cutting edges (S_t)

This plot was created for each of the cutting conditions and species.

The y-intercepts of all the cutting conditions and species can be seen in Fig. 9. Here, the R^2 value as well as the exact y-intercept is displayed above each bar. F_{II} of Scots pine is considerably higher than that for Norway spruce. This is likely due to the higher density between the species, as can be seen in Table 1. Although at a maximum major cutting edge, the cutting force of Scots pine is also significantly higher than that of Norway spruce due to the density differences. In both Norway spruce and Scots pine, F_{II} of frozen wood is lower than that of non-frozen wood. This is likely due to a lower elastic spring-back. Reduced elastic spring-back means that there is less contact between the minor cutting edges and minor first flanks and therefore less Zone II cutting. Furthermore, it is likely that the more brittle frozen wood broke on first contact with the tooth as opposed to non-frozen wood which likely bent and made more contact with the sides of the tooth during first contact. For both Norway spruce and Scots pine, F_{II} was a higher when cutting in dry wood. In Norway spruce F_{II} was remarkably higher. The R^2 value is also uncharacteristically low. Upon closer examination of the data, it seems that the cutting force of tooth no. 5 ($S_t = 2.2$ mm) did not follow the trend and was significantly higher than the cutting force of the other cutting teeth. This is likely due to some defect in the wood such as the beginning or end of a knot. If the contribution of tooth 5 is ignored, the R^2 value of the model becomes 0.82, but the y-intercept, and hence F_{II} of dried Norway spruce remained significantly higher ($F_{II} = 29$ N). The increase in F_{II} of dried wood could be because as the dry wood springs back, the fibres are broken off by the minor cutting edges instead of bent over which is likely the case in high moisture content wood where the fibres are less rigid and naturally cool the tooth. Furthermore, the high mechanical properties of dried wood likely result in higher cutting forces.

In Fig. 10, the Zone II force contribution can be seen with respect to the major cutting edge. For Norway spruce, the dried wood has a very high percentage of Zone II cutting. The Zone II force contribution to the cutting force is up to approx. 75% at a major cutting edge of 1.6 mm. The scatter in the dried Norway spruce is also higher than that of the other conditions. The reason for this high degree of Zone II cutting can be explained by the high mechanical properties of dried wood. Scots pine and Norway spruce follow similar trends with dry wood

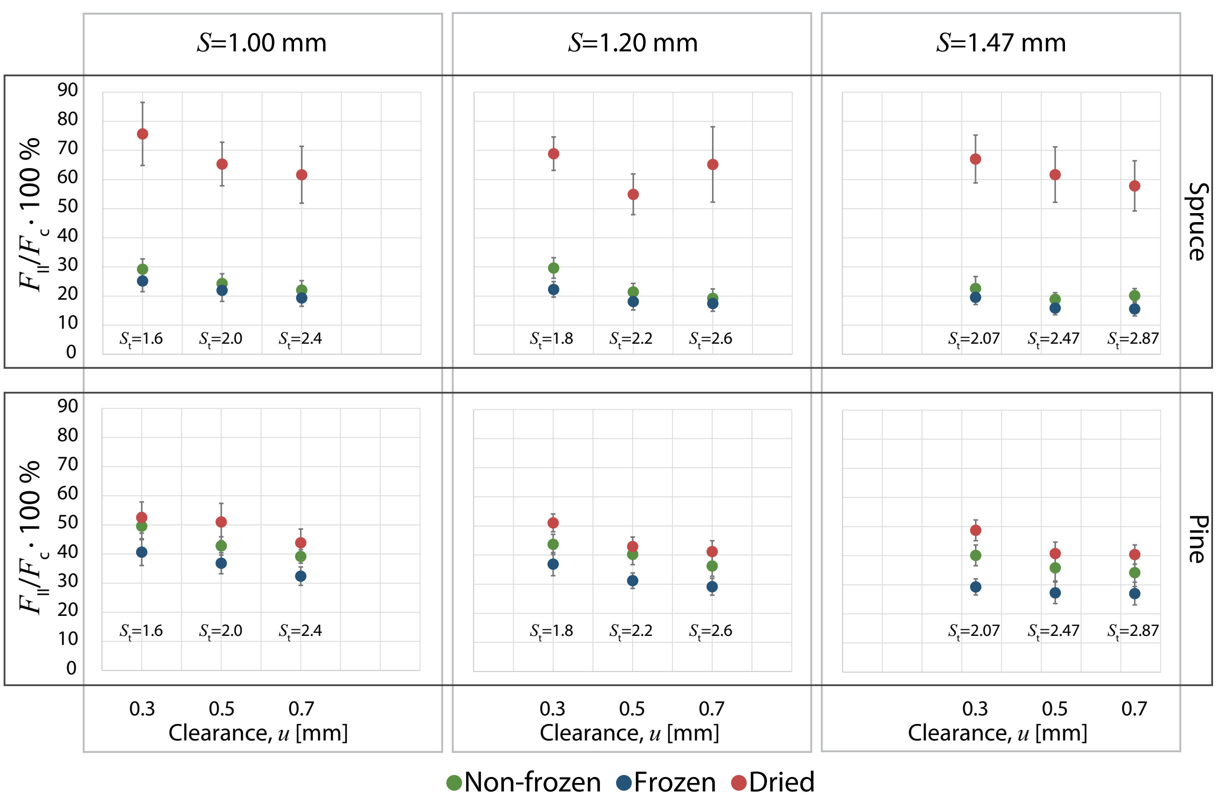

Fig. 11 The Zone II force contribution to the cutting force for different band thicknesses ($S = 1.47$, 1.20 and 1.00 mm) as the clearance is reduced ($u = 0.7$, 0.5 and 0.3 mm)

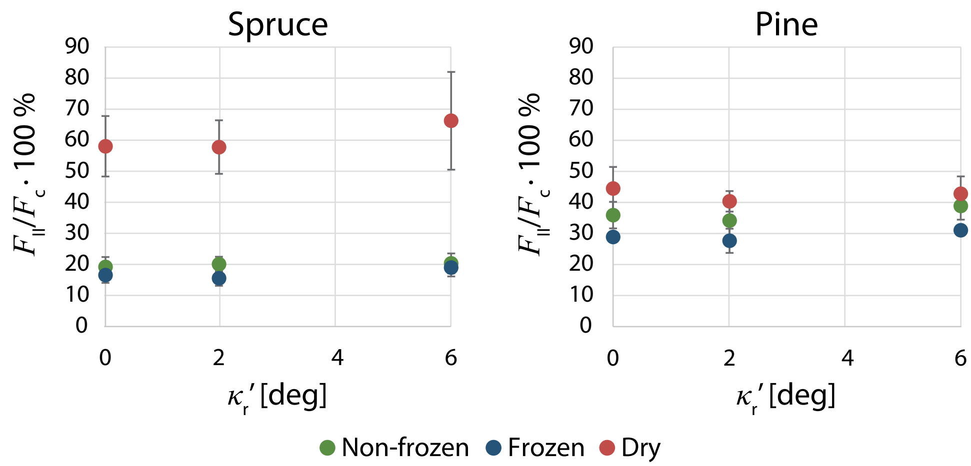

Fig. 12 The Zone II force contribution to the cutting force for with varying minor cutting edge angles (κ_r')

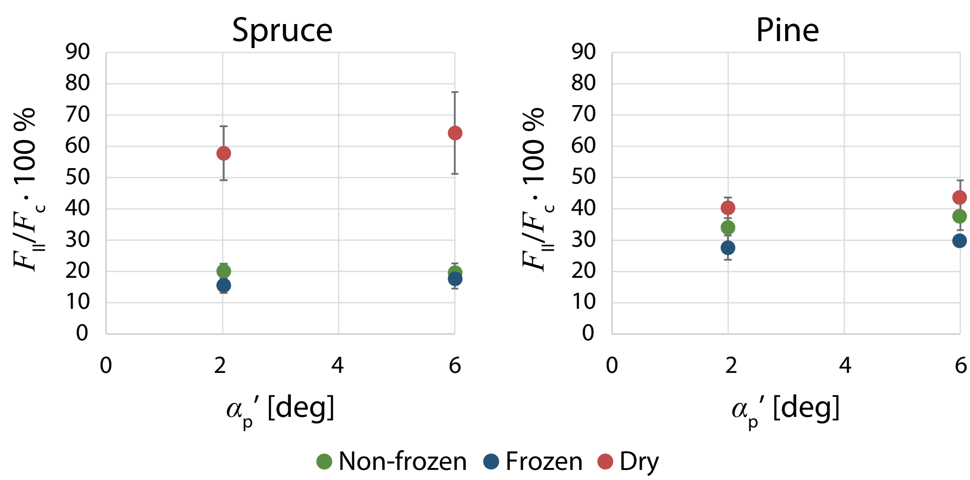

Fig. 13 The Zone II force contribution to the cutting force for with varying minor cutting edge angles (α_p')

having the highest ratio of Zone II cutting, followed by non-frozen wood and the least Zone II cutting percentage can be seen for frozen wood. Frozen wood has less elastic spring-back, and therefore also less contact between the minor first flanks of the teeth and wood. The percentage of Zone II cutting reduces with increasing major cutting edges. This is as the Zone II cutting does not reduce with a lower width and the uncut chip thickness is constant, but the major cutting edge does reduce and therefore also the force that acts on it. Therefore, it is logical that the ratio of minor cutting edge cutting to major cutting edge cutting increases. The percentage of Zone II cutting decreases when the major cutting edge is larger. When the industry is moving towards thinner bandsaws, it is important to consider this factor as the increase in Zone II cutting percentage can be up to 15% with a maximum Zone II cutting percent between 25 and 75 for the different conditions. When the Zone II cutting contribution increases, the wear behaviour of the cutting teeth as well as the temperature distribution in the tooth can change, which could lead to tooth failure and instabilities during sawing.

The percentage of cutting with Zone II when the clearance is changed for the three-band thicknesses can be seen in Fig. 11. Here, it can be seen that a lower clearance results in a higher percentage of Zone II cutting. This is the case for all wood conditions and for the three different band thicknesses. An approximate 10% difference can be seen between a clearance of 0.3 and 0.7 mm. A lower clearance means less room for wood that has sprung-back elastically which results in a higher friction force ($F_{cS'\mu}$). The Zone II cutting is as between 40–55% for dried Scots pine. This is significantly higher than the 7% Zone II force contribution that Li et al. [3] found in the same cutting direction. Li et al., however, tested a different species (birch—*Betula* spp.), different moisture contents (12%), with different tooth geometries and at uncommonly low cutting speeds (0.17 m/s). Furthermore, the model used to determine the Zone II cutting in this work does not take different clearances into account.

Series 2: minor cutting edge angle, κ_r', and minor cutting edge clearance angle, α_p'

κ_r' and α_p' largely affect the geometry of the minor first flanks of cutting teeth. A low κ_r' can result in a better surface quality of the wood, but it also exposes the minor cutting edges to a larger amount of elastic spring-back, which could increase the cutting force. A low α_p' leaves less room for the elastic spring-back which could increase friction, temperature and the cutting force. The Zone II force contribution for different κ_r' can be seen in Fig. 12. There is a slight increase in Zone II force contribution at higher κ_r', but considering the standard deviation, it can be said to be minimal. This indicates that such small angle deviations do not largely affect the Zone II contribution or the cutting force. At larger angles, the tooth becomes difficult to grind and the tooth shape is very sharp, leading to faster wear and increased vibrations.

The Zone II force contribution to the cutting force with different α_p' can be seen in Fig. 13 for Norway spruce and Scots pine. It was expected that the Zone II force contribution would be lower at high angles due to increased contact between the tooth and the workpiece, but there is a slight increase in Zone II force contribution at higher minor cutting edge clearance angles. The increase is, however very slight.

Conclusion

The cutting force can be split into two parts: Zone I major cutting edge force and Zone II minor cutting edge forces. This research investigated the contribution of Zone II forces to the cutting force when conducting single tooth cutting force tests in wood. Zone II forces are the forces acting on the minor cutting edges and the frictional forces acting on the minor first flanks. Tests were conducted in Norway spruce and Scots pine in dry, non-frozen and frozen heartwood. The main conclusions that can be drawn from the research are:

- Non-frozen wood has significantly higher elastic spring-back (up to 0.4 mm) than frozen wood and Norway spruce has slightly more elastic spring-back than Scots pine.
- In general, the cutting force of non-frozen and frozen wood have similar contributions from Zone II forces. Non-frozen wood has a slightly higher Zone II force contribution (when analysing the y-intercepts of the force–width plots) due to a higher degree of elastic spring-back. Frozen Norway spruce has the lowest Zone II force contribution of 8.2 N which is approximately 15% of the cutting force.
- The percentage of Zone II cutting increases up to 15% when decreasing the major cutting edge. For dried wood, the Zone II cutting contribution can be between 55 and 75% for Scots pine and Norway spruce, respectively. This is a significant part of the overall cutting force and should be considered when sawing with narrower teeth.
- An increase in minor cutting edge angle and minor cutting edge clearance angle resulted in a slightly higher contribution from Zone II cutting.

When considering these conclusions, it is important to keep in mind that the workpiece material is wood which is highly anisotropic. Furthermore, monitoring the cutting process concerns more than just the analysis of cutting forces. Other aspects such as temperature, vibrations, surface quality of the workpiece, etc., should not be neglected in broader studies. To better estimate the Zone II force contribution from a linear best-fit line, it is recommended to test cutting teeth where the clearance is kept constant while only the major cutting edge is reduced. These models can be compared to results where cuts are made on a ridge (open cuts, where the minor cutting edges are not in contact with the teeth at all) so that there is no Zone II cutting and only Zone I cutting. It could also be interesting to study the effect of uncut chip thickness on the Zone II forces.

Acknowledgements
The involved partners are thanked for their support. The authors gratefully acknowledge the support of CT WOOD—a centre of excellence at Luleå University of Technology for the development of X-ray computed tomography applications for use in the forest products industry.

Authors' contributions
VM and ME planned the research. VM carried out the experimental work and wrote the manuscript. All authors contributed to the discussion of the results. All authors read and approved the final manuscript.

Funding
Open access funding provided by Lulea University of Technology. The strategic innovation program, BioInnovation under Grant [2017-02697]—a joint venture by Vinnova, Formas and the Swedish energy agency (Energimyndigheten)—provided financial support as part of the IPOS project (Swedish wood—Innovation potential for the bio-based society), as well as the BioInnovation project: NGenTools.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

Declarations

Competing interests
No potential conflict of interest was reported by the authors.

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Received: 10 November 2021 Accepted: 17 February 2022
Published online: 19 March 2022

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