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Sustainability of cutting frozen wood - an analysis of buzz saw blades cutting performance depending on wood temperature

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Abstract

Sawing processes in sawmills are characterized by high consumption of electric energy. As cutting tools with geometrically defined cutting edges, circular buzz saw blades have a direct influence on cutting performance and thereby on the electric energy consumption of the cutting process. Thus, energy efficiency is directly linked to cutting forces, which are determined by the geometry of the saw-tooth and the material properties. In this paper, the energy consumption within cutting frozen wood at sub-zero temperatures is analysed. Results are presented and will lead the development of geometries for saw teeth to increase the sustainability of cutting frozen wood.

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Keywords: Wood Temperature, Sustainability, Cutting frozen Wood.

1. Introduction

The processing of frozen wood has always been a challenge for sawmills [1]. In times of increasingly scarce resources, high price sensitivity of customers and a need for sustainable products, it becomes more and more important for sawmill operators to achieve resource and cost efficient machining processes [2].

The machining of wood with a geometrically determined edge has been investigated in the past in numerous research projects. In the literature, the property changes of frozen wood and the challenges while machining (e.g. with circular buzz saw blades) are known for a scope of applications, but the present studies do not provide a holistic understanding of the effect of increased cutting forces while machining frozen wood. [1, 3–10]

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2. State of the scientific knowledge and need for action

2.1. State of the scientific knowledge

In literature, different effects can be found describing the behavior of machining frozen wood. The studies detect increasing cutting forces and decreasing cutting performance when sawing frozen wood.

Vazquez-Cooz and Meyer [8] conducted cutting tests on wood from sugar maple and red maple in various humidity and temperature levels. The study shows that dried wood requires higher cutting forces than greenwood, while for frozen wood the cutting forces are the highest. Besides Vazquez-Cooz and Meyer, Kivimaa and Kollmann and Côté [8–10] reason the cutting resistance of frozen wood to the frozen water in the logs. The water could lead to ice crystals in the plant cells which might cause the increased cutting resistance. Referring to Ilic [5], Kubler et al. [4] and Shmulsky and Shvets [3] the transformation of water into ice within the cell wall can facilitate a migration of moisture from the cell wall into frozen lumen water. The transformation leads to an expansion in the lumen. This effect - depending on the type of wood - makes the structure more rigid.

Vazquez-Cooz and Meyer [8] carried out additional tests on ice blocks at the same temperature as the frozen wood. They have shown the cutting forces for sawing ice are less than for frozen wood.

M. Ispas and M. Câmpean present a study for machining frozen and unfrozen wood from spruce with a circular buzz saw blade. In their study, the specific cutting resistance and electric power consumption are lower for frozen than for unfrozen wood. The authors relate this phenomenon to their use of saw blades with comparatively smaller diameters and lower processing depths a_e. Leading to a geometry where chips, dust and water are transported faster off the kerf. As a result, less material can get stuck between buzz saw blade and wood and the frictional resistance drops accordingly. [7] In the literature it is known that when scaling cutting tools, scale effects during chip removal can influence the machining process. [11, 12]

A further observation is made by Szmutku et al. [13]. The authors subjected spruce to a temperature treatment and analysed the strength values of the wood afterwards. They show that freezing rate can have a significant influence on the strength properties of wood. At a low freezing rate of -1 K/h, the wood shows reduced strength properties by up to 31 % compared to a freezing rate of -10 K/h. In this case, the strength properties are only reduced by up to 6 %.

2.2. Need for Action

The authors of the presented studies show that processing properties of wood can change at sub-zero temperatures [1, 3–10, 13, 14]. Unfortunately - due to different results of the studies - the cause of the increasing cutting forces when sawing frozen wood cannot be conclusively attributed to the scale effects, the cooling rate or the combination of cutting and fiber direction.

To close the identified research gap, in this study a comparatively small buzz saw blade is used and the cutting directions are carried out radial as well as tangential to the fiber direction of the wood. Additionally, the experiments are performed with frozen, thawed and green wood to identify the cutting performance of a buzz saw blade depending on wood temperature.

3. Experimental setup

3.1. Preparation of test specimens

For the experiments, a spruce log from Germany which is felled in winter 2016 is used. Immediately after delivery to the sawmill, the log is sawn to beams with dimensions of 600x67x87 mm.

Afterwards, four beams are cooled down in a cooling cabinet to -30° C, two beams are stored unfrozen in a closed plastic bag at 20° C as green wood. After 168 hours, two frozen beams are removed from the cooling cabinet and are thawed for 24 h at 20° C. All wood beams are cut from one single log. Based on these six beams cutting tests are

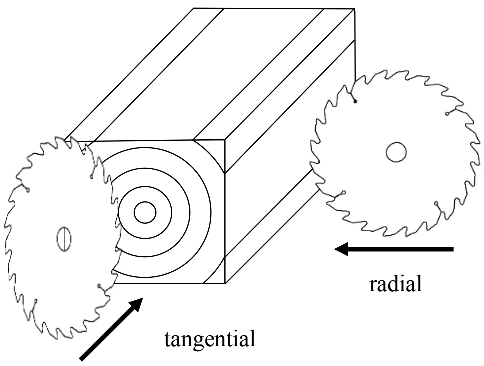

Fig. 1 Scheme of tangential and radial cutting directions.

performed to compare results with frozen, thawed and green wood. In order to determine the moisture, the beams are cut through in the middle, test specimens are removed and the wood moisture is defined according to EN 13183-1:2002. A Memmert UF-55 oven and scale from Waagen Nerreter GmbH, type Kern ALJ are used to determine the parameters. The moisture level of all beams are between 21 % and 23 % so it can be assumed, the beams had similar conditions. The experiments are carried out radial as well as tangential to the fiber direction of the wood. For a scheme of the cutting directions see figure 1.

3.2. Experimental procedure

The experiments are conducted on a Festool KS120 miter saw. The saw is constructed to move the saw blade manually together with the drive on a ball-bearing carriage. The specimen is clamped on the machine table for the purpose of sawing by moving the carriage in the direction of the specimen. A freely adjustable weight is connected to the carriage so the feed force F_f of the buzz saw blade is constant during the experiments. The used buzz saw blade has a negative rake angle γ because frozen wood shows hardness parameters like minerals or metals [16]. Based on these hardness parameters, a negative rake angle is more suitable then a positive one [15].

At the beginning of the experiments, 24.5 N are used as feed force F_f, afterwards it is increased twice about 30 % to 31.9 N and 41.4 N to compare the electric input P_{el}, electric power consumption W_{el} and average machining time t_m, see also table 1.

Table 1. Parameters of experimental setup.

Wood	Feed Force Setup			Analyzed Parameters		
Frozen spruce	24.5 N	31.9 N	41.1 N	electric input P_{el}	machining time t_m	electric power consumption W_{el}
Thawed spruce	24.5 N	31.9 N	41.1 N	electric input P_{el}	machining time t_m	electric power consumption W_{el}
Green spruce	24.5 N	31.9 N	41.1 N	electric input P_{el}	machining time t_m	electric power consumption W_{el}

The electric input P_{el} of the miter saw is recorded by an electronical network analyser from Chauvin Arnoux. It is put into place between miter saw and power supply network in order to document the electrical parameters during the experiments, figure 2 is showing the schematic setup.

At the beginning, the beams are sawn into smaller pieces, so the entire beams did not thawn during the experiment. For the tangential cuts, a piece of the beam is cut off and sawn to the same size as the specimen of radial cuts, so radial and tangential cuts use the same dimensions of specimen. For each parameter setup, ten cuts are performed and the averages for electric input P_{el}, electric power consumption W_{el} and machining time t_m are calculated. The degree of efficiency of the electric motor is not included in the calculations. The technical parameters of the experimental setup are listed in table 2.

The machining time t_m is determined on the electric input P_{el} of the miter saw, the electric power consumption W_{el} is calculated (1).

$$W_{el} = \frac{P_{el} \cdot t_m}{3,600} \quad (1)$$

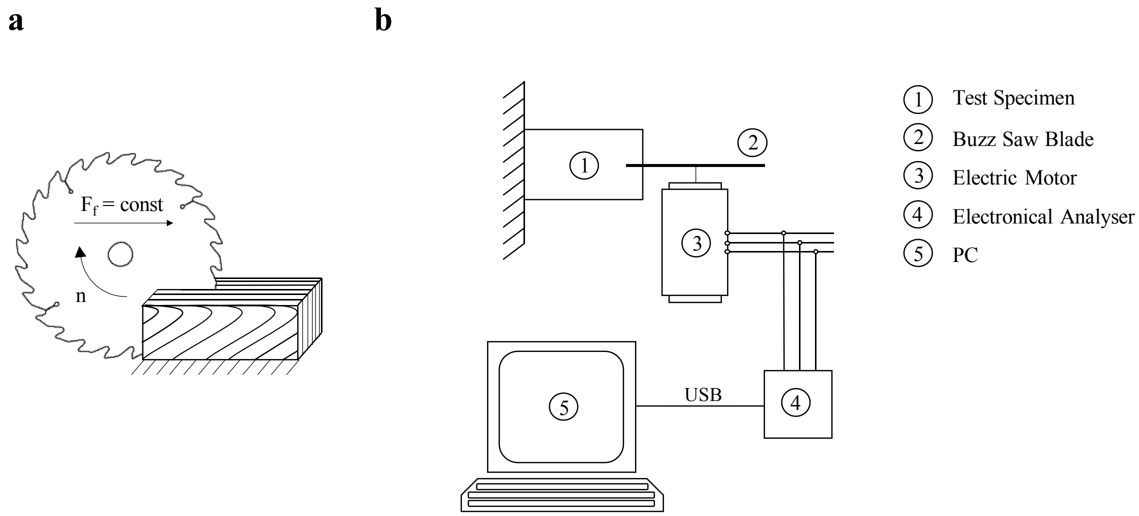

Fig. 2 (a) Kinematic of experimental setup; (b) Interconnection of electrical network analyser.

Table 2. Technical parameters of experimental setup.

Feature	Dimension
Miter Saw	
Model	Festool; Kapex KS 120
Revolution n	3,400 min^{-1}
Motor Power	1,600 W
Buzz Saw Blade	
Model	Festool, 494 607
Diameter d	260 mm
Thickness t	2.4 mm
Number of Teeth z	68
Pitch of Teeth	unbalanced
Clearance angle α	17°
Wedge angle β	79°
Rake angle γ	-6°
Electrical Analyser	
Model	Chauvin Arnoux; C.A 8335
Electricity Clamps	MN93A
Sampling Rate	256 Hz calculating an arithmetic average

4. Results and discussion

The evaluation of the test results shows differences between the tangential and radial cutting directions, the radial cutting direction over all cuts takes an average machining time t_m of about 10 seconds, for radial cuts about 4 seconds. Additionally, the average electric power consumption W_{el} over all cuts for tangential cutting direction is about 13 % higher compared to the radial cutting direction. For tangential cutting directions, this leads to an average electric power consumption W_{el} of 3.29 Wh which means, the tangential cuts consume 2.37 times more electric power than radial cuts over all feed forces F_f and test specimen. Additionally, for frozen wood the electric input P_{el} of the miter saw is highest in both tangential and radial cutting directions. Furthermore, the average machining time t_m of all cuts in tangential cutting direction exceeds the average machining time t_m of radial cutting direction by a factor of 2.15.

For feed force F_f of 24.5 N, the electric input P_{el} and the machining time t_m of sawing frozen wood in a tangential cutting direction is similar to the values of thawed wood. In a radial cutting direction, these effects cannot be confirmed. Here, the parameters of the green and the thawed wood are similar. The electric input P_{el} is the lowest for cutting green wood in tangential and radial cutting direction, the details are shown in table 3.

Table 3. Results for feed force F_f 24.5 N.

Parameters	Frozen spruce	Green spruce	Thawed spruce
Tangential cutting direction			
Electric input P_{el}	1,194 W	1,059 W	1,203 W
Machining time t_m	16 s	10 s	15 s
Electric power consumption W_{el}	5.31 Wh	2.94 Wh	5.01 Wh
Radial cutting direction			
Electric input P_{el}	1,170 W	1,064 W	1,146 W
Machining time t_m	9 s	4 s	5 s
Electric power consumption W_{el}	2.93 Wh	1.18 Wh	1.59 Wh

The increase in feed force F_f by 30 % from 24.5 N to 31.9 N leads to different results. Here, the electric power consumption W_{el} in tangential cutting direction is similar for green and thawed wood with 2.76 and 2.74 Wh. Additionally, the machining time t_m is the same with 8 seconds. Increasing the feed force F_f from 24.5 N or 31.9 N for cutting thawed wood in tangential cutting direction, the electric power consumption W_{el} decreases from 5.01 Wh to 2.74 Wh, which offers a saving of 2.27 Wh without significantly increasing electric input P_{el}. In this case, the machining time t_m can be reduced by 7 seconds (53 %). For cutting frozen, thawed and green wood in radial direction and increasing feed force F_f from 24.5 N to 31.9 N, the electric power consumption W_{el} can be reduced by 59.6 %, 22.9 % and 25.6 %, respectively, which is based on shorter machining times t_m. Table 4 shows the results for using 31.9 N as feed force F_f.

After increasing the feed force F_f again to 41.4 N, the machining time t_m for cutting frozen wood in tangential cutting direction took 5 seconds, which is 2 seconds less than for green or thawed wood at the same feed force F_f.

These results show a contrasting correlation when compared to the experiment results at 24.5 N and 31.9 N feed force F_f. Additionally, the electric input P_{el} of 1,313 W for cutting frozen wood in tangential direction is the lowest compared to cutting thawed and green wood. Referring to the literature, the electric power consumption W_{el} should be the highest in this case. The electric input P_{el} and the short machining time t_m lead also to the lowest electric power consumption W_{el} compared to green and thawed wood. Analysing the results of the radial cutting direction shows the effect, that all machining times t_m are the same as in these experimental setup using 31.9 N as feed force F_f. Only the electric input P_{el} increases by about 50 W to 80 W, so the electric power consumption W_{el} increases in a small range too, see also table 5.

Table 4. Results for feed force F_f 31.9 N.

Parameters	Frozen spruce	Green spruce	Thawed spruce
Tangential cutting direction			
Electric input P_{el}	1,295 W	1,242 W	1,235 W
Machining time t_m	10 s	8 s	8 s
Electric power consumption W_{el}	3.60 Wh	2.76 Wh	2.74 Wh
Radial cutting direction			
Electric input P_{el}	1,064 W	1,056 W	1,105 W
Machining time t_m	4 s	3 s	4 s
Electric power consumption W_{el}	1.18 Wh	0.88 Wh	1.23 Wh

Table 5. Results for feed force F_f 41,4 N.

Parameters	Frozen spruce	Green spruce	Thawed spruce
Tangential cutting direction			
Electric input P_{el}	1,313 W	1,412 W	1,381 W
Machining time t_m	5 s	7 s	7 s
Electric power consumption W_{el}	1.82 Wh	2.75 Wh	2.68 Wh
Radial cutting direction			
Electric input P_{el}	1,143 W	1,128 W	1,155 W
Machining time t_m	4 s	3 s	4 s
Electric power consumption W_{el}	1.27 Wh	0.94 Wh	1.28 Wh

The overview of the experiment results shows that higher feed forces are leading to more sustainable sawing processes for tangential cuts. The electric power consumption W_{el} increased in this case by an average of 8.1 % as the feed force F_f increased from 31.9 N to 41.5 N, but due to the shorter machining times t_m, the measure had a positive effect on the average electric power consumption W_{el}, which is reduced by 25.5 %. The radial cuts shows for an increase of feed force F_f from 31.9 N to 41.4 N an increase of electric power consumption W_{el} of 5.8 %. These results show a contrasting correlation when compared to the effects of tangential cuts. Additionally, the parameters for the electric input P_{el} shows a declining trend for radial cuts, while for radial cuts a trend could not be identified. Furthermore, the average machining time t_m of all tangential cuts is 60 % and for radial sections even 125 % higher than average values of green wood.

The results also show, that a feed force F_f of 24.5 N is not sufficient to ensure suitable cutting conditions for the presented setup. If the feed forces F_f are too low, the cutting edge is not able to cut into the work piece, which leads to significantly increasing machining times t_m.

5. Conclusion and outlook

5.1. Conclusion

In this paper, beams of spruce wood with different temperatures are cut by a circular buzz saw blade while using different feed forces F_f. The testing specimen, six samples of one spruce log, are cut in uniform beams and four of them are frozen to - 30° C, afterwards cutting tests are performed with frozen, thawed and green wood.

In the experiment, the feed force F_f is increased twice by 30 %, the electric input P_{el} and the machining time t_m of the miter saw are recorded, documented and analysed and the electric power consumption W_{el} is calculated. The analysis of the results shows that the electric input P_{el} increases along increasing feed forces F_f, while the machining time t_m and the electric power consumption W_{el} decreases.

The effect of increasing machining times t_m is significant for frozen and thawed wood in tangential and radial cutting direction, for green wood an increase of the machining times t_m cannot be observed on that level. It can be assumed, that circular buzz saw blades in industrial usage should be designed only for tangential or radial cutting directions to ensure a reduced electric power consumption W_{el} and hence, ensure sustainable sawing processes. The differences between cutting green and thawed wood should be analysed in more detail in further studies.

Furthermore, the evaluation of the experiments as well as the literature review show the optimization of single process parameters can neither provide economic advantages nor reduction of electric power consumption W for the optimization of single process parameters.

This paper provides support for the energy-efficient adjustment of industrial machining processes with circular buzz saw blades. Additional researches with finer granular and a further scattered experimental parameterization and additionally a fine granular variation of cutting geometry parameters should be carried out to refine the present results.

5.2. Outlook

For future investigations, cutting forces and theoretical chip thickness while cutting frozen, thawed and green wood should be analysed by using alternating cutting geometries. Additionally, different cutting geometries should also be used to analyse the influence of the electric power consumption W_{el} of the feed drives.

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