Forces Acting on Saw Teeth during Timber Processing - A Practical Approach

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Two oak cant timbers were sawn up to a total of 58 boards. As a dependent variable, the energy consumption while manufacturing a board was measured. As influencing variables, timber and saw blade characteristics were assessed, including density, moisture content, log feed speed, blade profile, and sawing sequence. Four types of forces acting in a saw-tooth were derived, namely, the dust particle shaving force, the particle accelerating force, the dust compressing force, and the frictional force as a consequence of blade wear. The experiment showed that the most prominent factor is the shaving force if the blade was newly sharpened, and that the dust accelerating and compressing forces were negligibly small. The frictional force grew from insignificant at the first board to more than one fourth of the force total at the 58th board. With each board, the saw tooth tips receded by more than 2 μm. With these data, the course of blades' deterioration from wear was characterised.

Keywords: Frictional force; Shaving force; Saw dust compaction; Saw blade wear

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INTRODUCTION

Sawing is one of the most often used timber processing technologies. As head rig, the band saw increasingly enjoys widespread usage in the industrial sawing practice. In recent years, the energy consumed during processing has become a central issue. It is well documented that the required energy increases as the cutting edge becomes dull (Kivimaa 1950; Aknouche *et al.* 2009). Naylor and Hackney (2013) stated that the primary mode of tool wear was abrasion. A worn tool has been found to cause excessive compaction of fibres just before cutting, and this affects process efficiency as well as product surface quality. Youn and Yang (2001) provided a method for an in-process assessment of tool condition. Ramasamy and Ratnasingam (2010) reviewed tool wear as a consequence of timber sawing.

Numerous investigations have been carried out to uncover the optimum conditions for wood machining. The results have confirmed that, in general, three factor-groups control the cutting mechanics (Méausoone 2001; Eyma *et al.* 2004; Moradpour *et al.* 2013): (1) machine characteristics, (2) timber species characteristics, (3) and processing conditions. Günay *et al.* (2005) found that the cutting force decreases with increasing rake angle. Porankiewicz *et al.* (2011) investigated the dependency of cutting forces on eight machining parameters during sawing.

Echeverri (2003) explored the lateral forces acting during sawing, causing the washboarding of lumber surface. With a set of orthogonal cutting force data, he developed

an analytical model to predict the magnitude and dynamics of cutting forces during band sawing. Ko and Kim (1999) worked out a cutting force model for band sawing by analysing the geometric shape of saw tooth and tooth-set patterns under various sawing conditions.

Cutting speed has been found to influence the shape of the chips and the sizes of sawdust particles (Sutter and Molinari 2005). Porankiewicz *et al.* (2006) examined the high-speed steel tool wear during wood cutting in the presence of high-temperature corrosion and mineral contamination.

In the present paper, an effort is made to develop a practical method that enables the engineer on the shop floor to derive useful data from the sawing activity. The engineer is concerned with the forces emanating mainly from tool wear, and is keen to determine the proper time for tool change, possibly with the help of an automatic reminder. Therefore, relying on the above literature survey, the present analysis will use only so much theory as is needed to establish the correctness and applicability of the method.

Four types of forces will be assumed to affect the saw blade, namely: the cutting force that separates the dust particles from the solid timber, the force accelerating the dust particles from the resting state to the saw blade's running velocity, the saw dust compressing force, which reaches its full effect at the moment the particles leave the log, and the friction force, which increases with progressing abrasion of the saw blade. Lateral friction forces will be neglected as long as the saw blade is properly set and not overstressed. This is the case at a proper production routine and also in this investigation.

The goal of this article is to describe a simple method for the determination of forces acting in a blade tooth while sawing, as well as to indicate the magnitudes of these forces and to rank them according to their relevance.

EXPERIMENTAL

In a laboratory work hall, the energy consumption was electronically recorded for all boards, manufactured with the help of a horizontal band saw machine (Forestor Pilous CTR650S, Czech Republic). The total energy uptake was then divided into the idle part of the energy, which kept the machine running, and the useful part of the energy, which produced the board.

As experimental material, two oak cant timbers with 2.5 m length - labelled as log 1 and log 2 - have been taken from the Hungarian Bakony Mountain. Each was sawn into 29 boards, all having widths of 0.2 m.

The measured variables were the energy consumption for the separation of a board (ranging from 7.36 to 26.6 W.h), the cutting time (ranging from 65.6 to 89.6 s), moisture content and density of each board (with an average of 56.4 ± 2.45[1] %, and 776.2 ± 36.2 kg/m^3, respectively), the blade running speed (25 m/s), the blade profile (tooth pitch 22 mm, gullet area 103.2 mm^2, saw kerf width 2 mm, blade material hard steel), and the sequence of sawing events, designated as sawing order, and labelled from 1 to 29 in each log. The sawing order, SO, has been used as a dummy for the increment of wear, and subsequently inserted in the statistical model as independent variable.

Calculated values were the gullet volume of a saw tooth (206.4 mm^3), log feed speed (ranging from 104.4 to 137.2 m/h), number of teeth leaving the log per second (1137

[1] All values preceded by the sign ± represent confidence limits at p=0.05, n=58

teeth/s), solid timber volume converted to dust in the saw kerf per board (0.0010 m^3), and the mass of sawdust cut away by one tooth (approximately 0.01 g).

Additionally, saw dust samples were collected to examine their volume collapse characteristics under load. To this end, in a steel cylinder, known amounts of saw dust from the collected samples, approx. 50 g, were subjected to increasing compression loads. The cylinder with known physical dimensions was placed into a standard testing machine which electronically registered the compressing force F_c with an accuracy of 0.001 N and the corresponding movement of the piston in 0.01 mm steps.

RESULTS AND DISCUSSION

The saw dust compacting force, F_c, was determined by compression tests, and the results are plotted in Fig. 1.

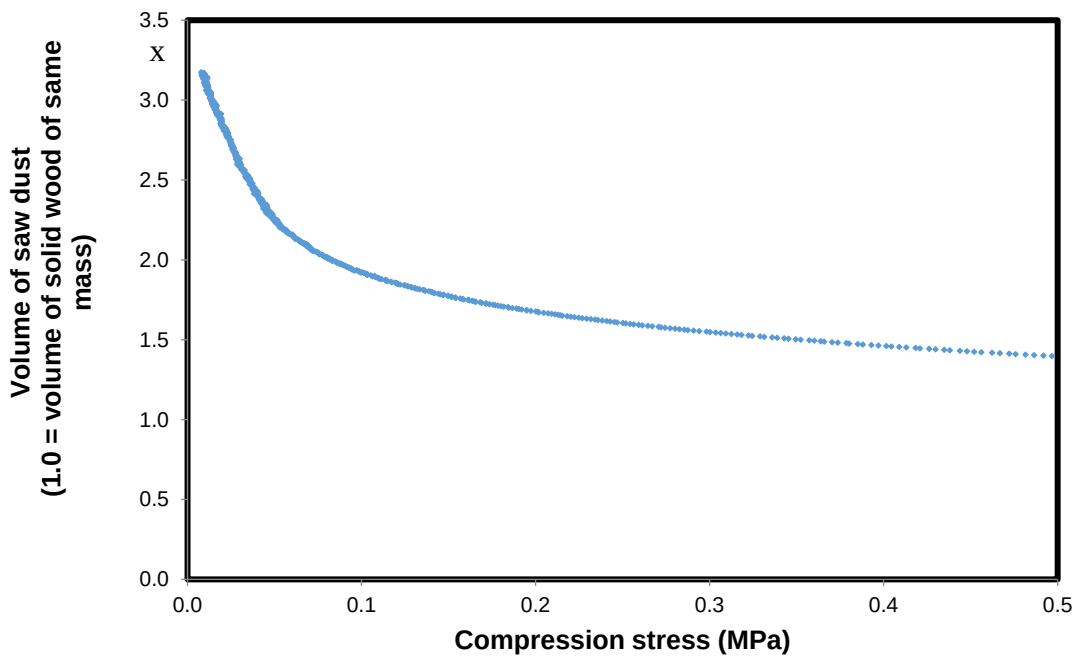

Fig. 1. Volume change of saw dust under compression load - fitting curve representing the mean of ten measurements

The points in Fig. 2 denote the amount of electrical energy needed to separate one board from the log in the experiment. This amount is equal to the sum of all forces, which shall be subdivided into components later, and is designated F_{tot}. Because the sawing order stands for the tool wear, a slow and steady increase of the dots would be expected. This is not the case, yet the red dots find themselves mostly above the blue ones. The distribution of the points leads to a presumption that other independent factors have a marked influence on the scatter of data.

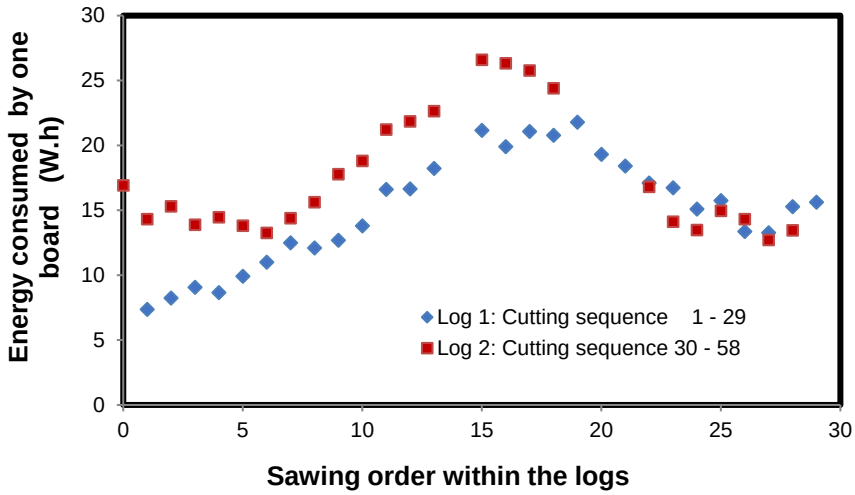

Fig. 2. Energy consumption needed to manufacture one board

The curved data course may be explained partially by a similar distribution of board densities (Fig. 3), and partially by moisture content (Fig. 4).

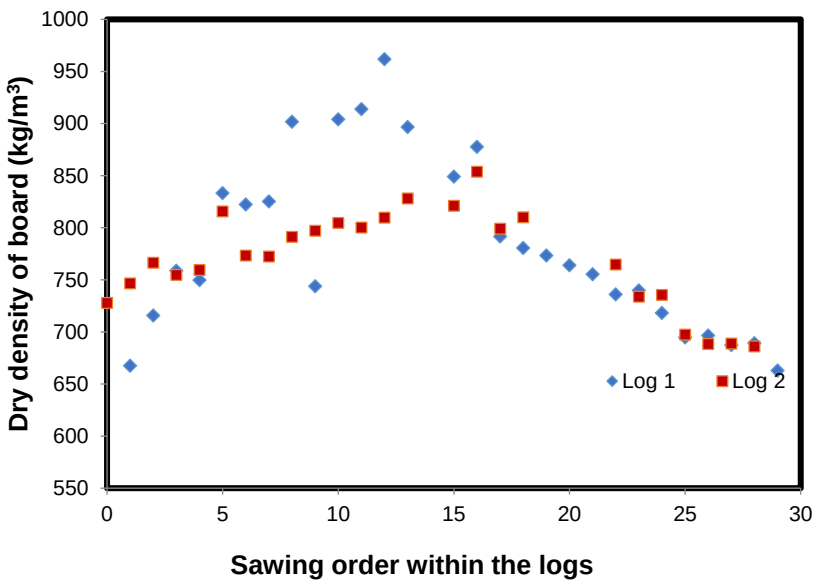

Fig. 3. Dry densities of boards in the two logs

For closer study, the useful part of the energy uptake was scaled down to the single tooth engaged in the process.

According to our working hypothesis, the four types of forces acting in the saw-teeth during timber processing are (1) the sawing or cutting force F_s, (2) the saw dust acceleration force F_a, (3) the saw dust compacting force in the gullets F_c, and (4) the force needed to overcome the increasing friction from wear F_w. From these four, the last three can be directly measured, and the fourth – the cutting force F_s (1) – is calculated as the difference between the first three and the total force F_{tot}, measured via the useful energy uptake. Below, they will be individually discussed.

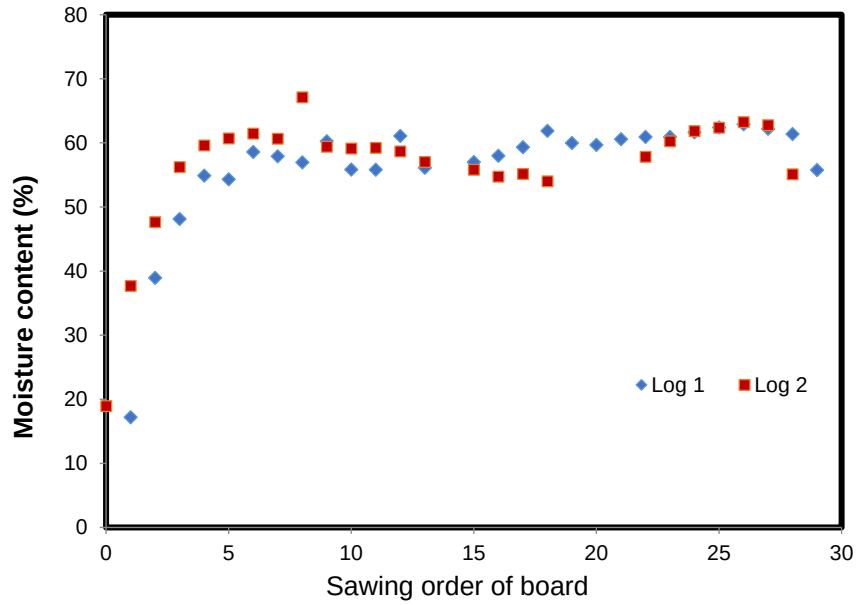

Fig. 4. Moisture content of boards within the two logs

Acceleration Force F_a

The dust acceleration force F_a can be derived from the impulse change (ΔI) that the saw dust experiences during the cutting event: The particles just being shaven from the solid wood will be accelerated from the resting state to the running speed of the saw blade.

The mass of oak saw dust in the gullet is approximately 0.01 g. The blade runs with a velocity of 25 m/s. Thus, the impulse change according to Eq. 1 is,

$$\Delta I = m \cdot \Delta V = \text{mass of saw dust in gullet} \cdot \text{velocity change} = 0.00001\ \text{kg} \cdot \left(25 - 0\,\frac{\text{m}}{\text{s}}\right) = 0.00025\ \text{kg} \cdot \frac{\text{m}}{\text{s}} \quad (1)$$

In the calculations it was taken into consideration that the gullet is empty at the instant of tooth entry and gradually fills. Thus, the impulse change was calculated for the half saw dust mass collected by a gullet during one passage through the log.

From the impulse change, the driving force F_a can be calculated using Eq. 2,

$$F_a = \frac{\Delta I}{t_H} \quad (2)$$

$$= \frac{\text{impulse change}}{(\text{ runtime } t_\text{H} \text{ of the tooth through 0.2 m cutting height })} = \frac{0.000\,25\ \frac{\text{m} \cdot \text{kg}}{\text{s}}}{0.008\ \text{s}}$$

$$= 0.0313\ \text{m} \cdot \frac{\text{kg}}{\text{s}^2}\,[=\ \text{N}]$$

In the final balance of forces, F_a shall be included with a value of 0.0313 N/tooth.

Compaction Force F_c

To determine the strength of the compacting force, the bulk density of the dust in the gullet should be estimated. In the previous paragraph, the mass of saw dust in the gullet was determined to be 0.01 g. Using this number, the volume density turned out to be a rather low value if compared with that of solid wood. More specifically, the volume of the

saw dust increased approximately 6-fold. Figure 1 stops short of this value. Thus, to calculate the compression force, a low compression stress reading on the horizontal axis of σ_c = 0.01 MPa was chosen for which data has existed. F_c is calculated using Eq. 3, where A is the cross-sectional area of the gullet (= blade_thickness × gullet_depth):

$$F_c = \frac{\sigma_c}{A} = \frac{0.01\ \mathrm{N/mm^2}}{1\ \mathrm{mm} \cdot 6.5\ \mathrm{mm}} = 0.0015\ \mathrm{N} \tag{3}$$

In the balance of forces below, the actual compression force F_c will be included with a value of 0.0015 N/tooth.

For practical purposes, the compaction of saw dust at this filling grade is negligible. For the sake of completeness – because here the method of calculation is demonstrated – it is still included in the equation which must be all-inclusive. At higher log feed speeds, of course, the compaction might become relevant.

Frictional Force F_w

The frictional force responsible for wear F_w cannot be directly calculated. It was approximated in four steps:

Firstly: The energy consumption for the separation of a board was measured (Fig. 2). From this energy intake, the value of the force total F_{tot} was derived according to Eq. 4:

$$F_{\mathrm{tot}} = \frac{\Delta E_{\mathrm{u}}}{H} \tag{4}$$

Here, ΔE_u is the measured total energy consumption at the actual moisture content in Watt.second and H is the cutting height (board width) in meter.

The corresponding numbers ranged from 1.825 to 7.00 N/tooth, exhibiting a similar data distribution as in Fig. 2.

Secondly: Factors have been identified that could possibly influence the total force needed to separate one board from the log. In the experiment, these factors have been measured or recorded for each board. Thereby, F_{tot} is the dependent variable which is the total of forces acting in a saw-tooth during sawing, and r_o is the dry density of board. Because matter is the carrier of properties, this is one of the most important intensive variables. *SO* indicates the sawing order of boards, actually standing for the wear of the saw-blade, which presumably increases with each sawing event. N^o is the log number, a categorical variable, taking the individuality of a log into account. The variable $u_{\%}$ is the moisture content. *LFS* is the log feed speed, which is kept at a constant and slow value to allow time for the collection of all relevant data. The variable ε is the error of estimates, which accounts for all unmeasured variables, such as the electrical loss angle (cosφ) or driving wheel revolution change under load or other.

The following interrelation among the variables was postulated (Eq. 5):

$$F_{tot} = f\ (r_o, SO, N^o, u_{\%}, LFS, \varepsilon) \tag{5}$$

The numerical values characterising the above interrelationship were statistically evaluated below.

Thirdly: A series of multiple regression computations have been carried out using the Eq. 5 as a working tool. The aim of the analysis was to estimate the weight of the

variables in the equation. The best fitting equation was then selected to predict the dependent variable - the force total - on basis of the abovementioned independent variables. The calculations were carried out according to Sokal and Rohlf (2011) using the "*Statistica*" software. Table 1 contains the numbers and the coefficients of the best model.

Table 1 shows that the selected multiple, non-linear regression model is reasonably accurate (*F*-test = 22.8 with a very low error probability *p*). The model explains 77% of the dependent variable's variation (R^2_{adj}). The computed partial regression coefficients predict the weight of influence of each independent variable on the dependent variable. They are the essential ingredients in Eq. 6 below:

$$F_{tot}\ [N] = -69.2 + 0.181 \cdot r_o + 0.000104 \cdot r_o^2 + 0.274 \cdot SO - 0.00196 \cdot SO^2 - 4.02 \cdot N^o - 0.0647 \cdot u_{\%} - 0.000111 \cdot u_{\%}^2 + 0.00776 \cdot LFS \pm 0.667 \quad (6)$$

The equation describes the above data set only; it does not have a general validity. Yet, it is central to this investigation. With its help, one can calculate the total force in dependence of all influencing variables. For instance:

$F_{tot.\ first\ board}$ = 2.190 ± 0.667 *N/tooth* and

$F_{tot.\ last\ board}$ = 4.908 ± 0.667 *N/tooth*

These values will be entered into the balance of forces (Eq. 7) and in Table 3.

The standardised partial regression coefficients (SPRC) determines the weight of each independent variable of the force total. More precisely, dry density explains approximately 72% of the variation of the dependent variable (=100*{0.375+0.343}; last column in Table 1), sawing order approximately 20%, log number approximately 6%, moisture content approximately 2%, and log feed speed only a fraction of a percentage. The last three variables do not seem to have any statistically significant influence on F_{tot}.

With these data in mind, the increase in friction force from wear F_w can be estimated, which has been the genuine purpose of this investigation. This is accomplished by analysing the standardised partial regression coefficients. When keeping all other independent variables constant, there will be a change by the amount of SPRC in the standard deviation of the dependent variable F_{tot} if the value of the selected independent variable - here sawing order - increases by one standard deviation. Expressed in numbers, the standard deviation of sawing order was 16.7, associated with a SPRC of 0.2736. Hence, after sawing 17 boards, the friction force would increase due to progressing bluntness by F_w=0.379 N (=1.3912*{0.2736 – 0.002/2[2]}). The entire experiment consists of 58 sawing actions, which corresponds to 3.46 standard deviation units. The according increase in force because of friction at the last board will be $F_{w.58}$ = 1.312 N (=3.46 * 0.379).

In the final balance of forces, $F_{w.58}$ is entered with a value of 1.31 (N/tooth).

Fourthly: Additional information can be gained from the pictures below. Figure 5 shows photographs of just sharpened teeth on the left side, and the same teeth after 58 cutting events on the right. The progress of wear is clearly visible. Five teeth were closely analysed. Table 2 displays the measured data (not a statistical sample).

[2] The second-order term with -0.002 is almost negligible, yet statistically still significant, and it is being taken into account. The divisor 2 accounts for the number of std. dev. steps of $u_{\%}^2$.

Table 1. Statistical Analysis

Independent variables IV	Means	Std. Dev. s_{IV}	Partial regression coefficients	Error probability *p*	Standardised partial regression coefficients SPRC	Relative weight of the IV
Intercept	…	…	-69.225	0.000'001	…	…
r_o	776.19	68.46	0.1810	0.000'001	8.9048	0.375
r_o^2	607063	108956	-0.0001	0.000'006	-8.1254	0.343
Sawing order	28.358	16.69	0.2736	0.000'00..	3.2805	0.138
Sawing order^2	1077.3	1008.8	-0.0020	0.000'010	-1.4241	0.060
N^o	1.4717	0.5040	-4.0170	0.000'00..	-1.4552	0.061
$u_{\%}$	56.4	9.28	-0.0647	0.3540	-0.4318	0.018
$u_{\%}^2$	3262.5	806.45	-0.0001	0.8870	-0.0643	0.003
Log feed speed	122.5	6.06	0.0078	0.681'0	0.0338	0.001
Dependent variable DV						
F_{tot}	4.9134	1.3912			Control:	1.000

F-test $_{8,44}$ =	22.8	p < 0.000‘001
R =	0.898	R^2_{adj} = 0.770
± ε =	0.667	
n =	53	

According to Table 2, the mean distance between the sharp and the blunt tooth tips is 132.2 µm. With each cutting event, the tooth tips regressed on average more than 2 µm. Also, the radius of curvature increased from 44.1 to 97.3 µm after 58 runs. With progressing wear, the radius of curvature at the tooth tip became accordingly larger, offering a larger surface to rub against, yielding the increasing frictional force.

Table 2. Selected Saw Teeth in Sharpened State and after 58 Sawing Events

Tooth code	T_1		**T_2**		T_3		**T_4**		T_5	
Entries	D	R	D	R	D	R	D	R	D	R
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm
Sharp	156	105	0	0	0	0	93.4	75.6	53.5	40.1
Blunt	273	187	122	85.8	128	90,5	192	150	249	194
Difference	117	82	122	85.8	128	90.5	98.6	74.4	195.5	153.9

Legend:
D - Distance (µm) between the tooth tips in sharpened and in blunt state as indicated in Fig. 5
R - Radius of curvature (µm)

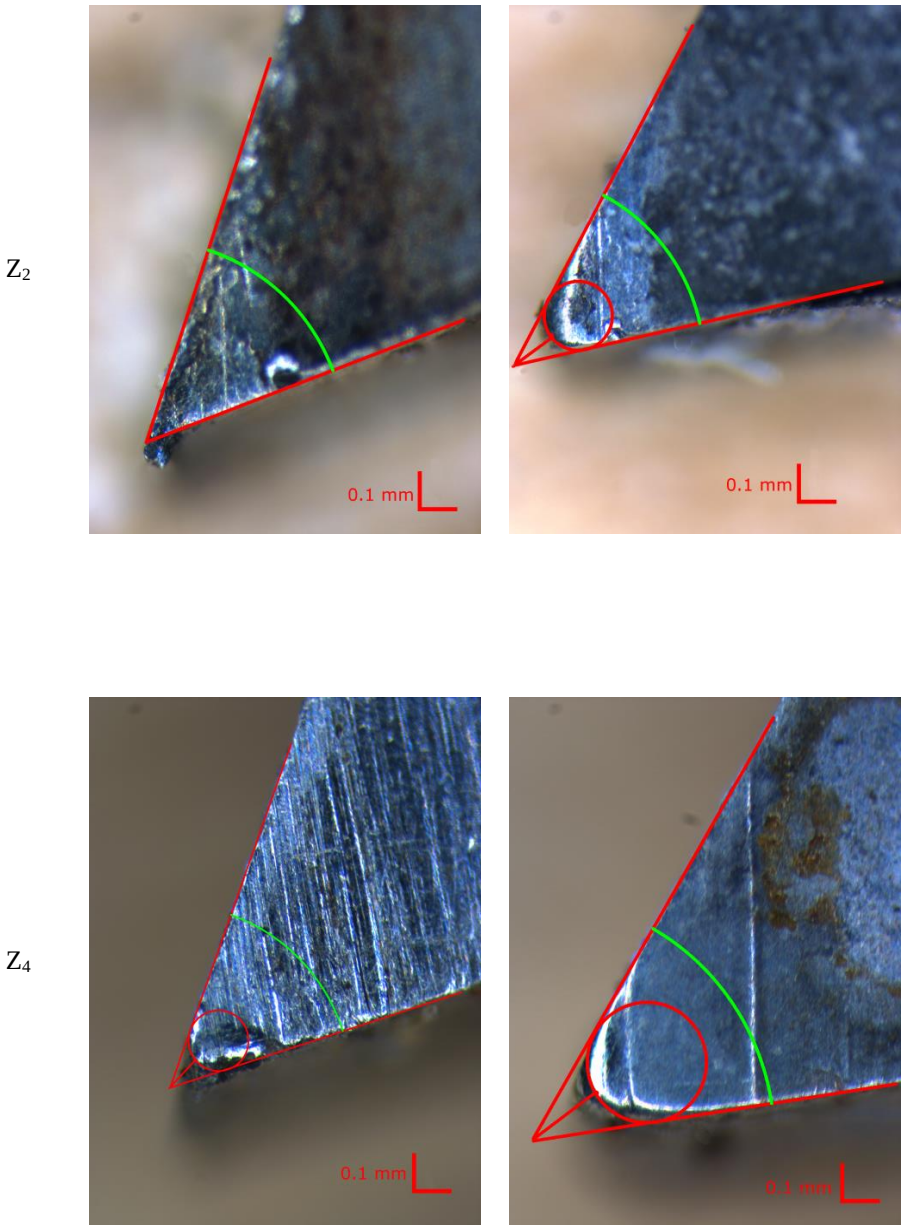

Fig. 5. Selected saw teeth: just sharpened (left) and after use (right)

The question arises as to how the hardened tooth tip can be worn off so speedily by a soft material such as wood. In the relevant literature there are reports on corresponding investigations stating that tooth tips, having a small radius of curvature, would get heated up by friction to temperatures surpassing 600 °C, even reaching 800 °C. This effect has been demonstrated by the changed chemical composition of the cutting edge material when analysed before and after sawing (Porankiewicz *et al.* 2006). At these temperatures, the tip material becomes soft enough to get physically worn off or possibly to sublimate.

Now, the balance of forces can be presented in Eq. 7:

$$F_{tot} = F_s + F_a + F_c + F_w \quad (7)$$

As a result of this study, true numbers can be associated with the forces explored. Table 3 gives a review of these numbers. The four force types are shown in column one. The second and third columns contain the force strength for the 1st board, followed by data; the 29th and the 58th boards are shown as an example. The force totals in the bottom row were calculated by the model Eq. 6. In this experiment it became obvious that the sawdust accelerating and compressing forces were negligibly small when compared with the cutting and friction forces.

Bariska and Pásztory (2015) have shown that at maximal permissible gullet filling irrespective of the timber species used (fir, beech, oak), the volume of compacted sawdust was approximately two times that of solid wood. Using this value in Fig. 1, the dust's bulk volume of 2 would correspond with a stress value of approx. 0.09 MPa. When calculated, the compacting force at optimum gullet filling would be 0.014 N, which is approximately 10 times our actual value, yet still a very small figure when compared with the other force types.

Table 3. Change of the Strength of the Various Force Types in a Saw Tooth During Sawing

	1st sawing		29th sawing		58th sawing	
Force types	N	%	N	%	N	%
Cutting force F_s	2.157	98.50	2.651	79.16	3.545	72.60
Accelerating force F_a	0.0313	1.43	0.0313	0.93	0.0313	0.64
Compacting force F_c	0.0015	0.07	0.0015	0.05	0.0015	0.03
Friction force F_w	0	**0.0**	0.665	**19.86**	1.31	**26.73**
Total of forces F_{tot}	2.190	100.0	3.349	100.0	4.908	100.0

Formulated in a more illustrative manner for the first sawing with sharp teeth:

100% Force_Total (2.190 N) ≈ 98.5% Cutting_Force +
1.4% Dust_Accelerating_Force + 0.1% Dust_Compression_Force +
0% Friction_Force (8)

At the first board, the friction force is assumed to be a minimum value, here denoted 0%. The effect of wear is about to start from here.

After 58 boards, the equation expresses the following situation:

100% Force_Total (4.908 N) ≈ 72.6% Cutting_Force +
0.6% Dust_Accelerating_Force + 0.03% Dust_Compression_Force +
26.7% Friction_Force (9)

The increase in the total force from 2.190 to 4.908 N was not caused by wear alone; it was rather the result of the entirety of the independent variables, such as the larger board density together with changes in the other influencing variables, upon which the effect of wear with 1.31 N is ultimately superimposed.

CONCLUSIONS

The purpose of the investigation has been achieved. A practically applicable method was presented for the determination of the four types of forces involved in sawing. It could be shown that the main forces were the cutting force and the increasing friction force causing bluntness, respectively. The acceleration force and the saw dust compressing force remained negligible in the whole sawing experiment.

In sawing practice, during a working shift, hundreds of boards are produced. At some stage, the force from growing friction will exceed the cutting force, rendering the production costs of timber processing unfavourable as the processing procedure slows down, and 50% or more of the useful energy will be needed to combat wear effects. In this example, the frictional force $\boldsymbol{F_w}$ will become equal to the cutting force $\boldsymbol{F_s}$ after the manufacture of approximately 120 boards. The time needed for the production of this amount of lumber is approximately 4 h, *i.e.*, half of a work shift time. When costs involved are known, the economics of blade sharpening schedules can exactly be computed. With the knowledge of the magnitude of actual forces involved, optimum production schedules can be elaborated.

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