Some fundamental aspects of wood chipping

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ABSTRACT: To improve chip quality with regard to chip dimensions and fiber damage, the mechanisms of chip formation must be better understood. Therefore, an experimental setup which can measure the cutting force in two dimensions in low-speed chipping was developed. The influence of clearance angle, bevel angle and chip length on cutting force, chip thickness:length ratio, and fracture mode was studied. It was discovered that the force component perpendicular to the movement of the knife could be quite high and that the clearance angle had a large effect on the resulting cutting force. The experiments revealed that chip formation is quite complicated, since the variables interacted in an unexpected manner. Thus a factorial experimental design is crucial in any study of wood chipping, because the response to a change in one variable depends on the values of the other variables.

KEYWORDS: Angles, bevels, chip dimensions, chipping, clearance, cutting, experimental design, fracture, force, knives, thickness, variables, wear, wood.

In most pulping processes, it is important that the wood chips be of high quality. Normally, a relatively thin chip with a minimum of fiber damage as well as a narrow chip size distribution is desired. In order to improve chip quality in terms of chip dimensions and fiber damage, the mechanisms of chip formation must be better understood.

The action of the disc chipper has been investigated extensively since it was invented by Wigger in 1889 *(1)*. Several studies have been performed on an industrial scale, but in order to understand the mechanisms controlling chip formation there are some fundamental investigations which are of particular interest. Kivimaa and Murto *(2)*, Hartler *(3)*, and Buchanan and Duchnicki *(4)* have photographed the chip formation and measured the cutting force component parallel to the movement of the knife. Hartler *(3)* performed the study at a relatively high cutting speed, 5–20 m/s, (industrial cutting speeds are normally 20–40 m/s) whereas the other investigations were performed at much lower cutting speeds (1 mm/s and 8 mm/s), which makes a direct comparison difficult. The force measurements of Kivimaa and Murto *(2)* and of Buchanan and Duchnicki *(4)* show that the cutting force increases as the knife penetrates deeper into the wood until a fracture is initiated, whereupon the cutting force decreases rapidly. Both Kivimaa and Murto *(2)* and Buchanan and Duchnicki *(4)* employed a clearance angle of 0 degrees, although it is normally 2–7 degrees in industrial chipping.

Kivimaa and Murto *(2)* and Buchanan and Duchnicki *(4)* also showed that a decrease from 40° to 30° in the knife angle reduces the cutting force, chip thickness and chip damage. A drawback of using a small knife angle is that the strength and durability of the knife edge are lowered, which gives rise to a higher dust content in the chips. Thus, it seems advantageous to combine the positive effects of knives with small and large angles by grinding a bevel on a knife with a small knife angle. This has been practiced industrially for a long time *(5)*, but how this af-

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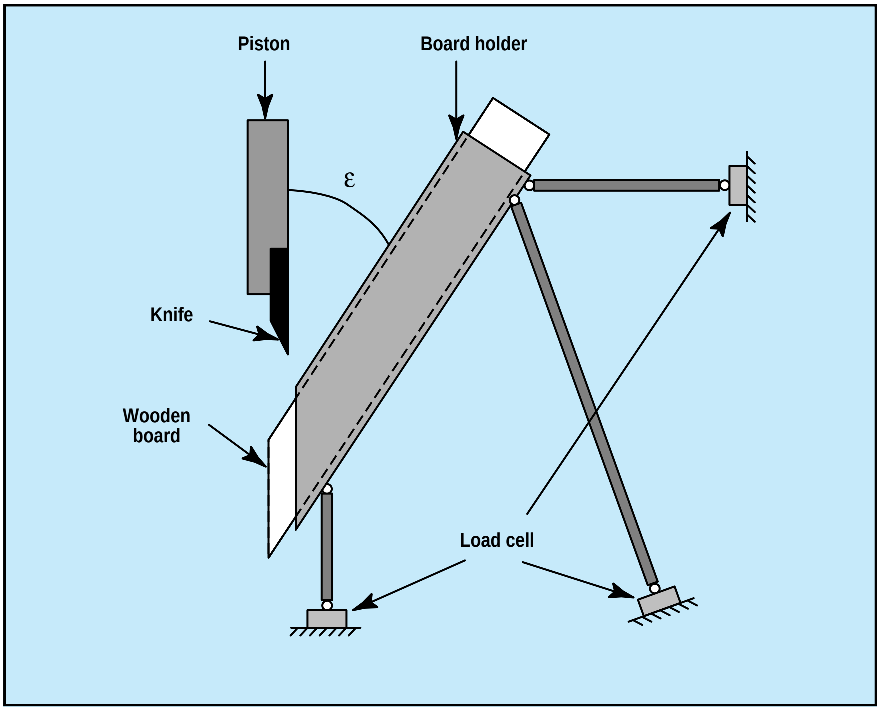
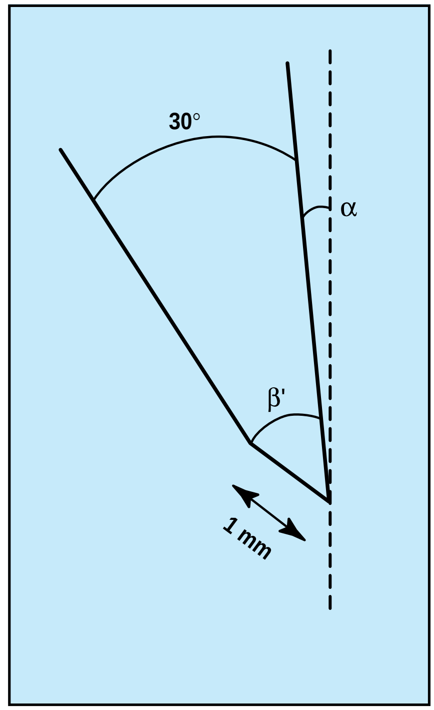
1. Diagram of the experimental setup



2. The bevel angle ß´ of the knife and the clearance angle α were varied in the trials.



fects cutting force and chip quality has not been thoroughly investigated.

The scope of this investigation has been to study the influence of clearance angle, bevel angle and chip length on the cutting force, the chip thickness:length ratio and fracture mode in order to gain a deeper insight into chip formation.

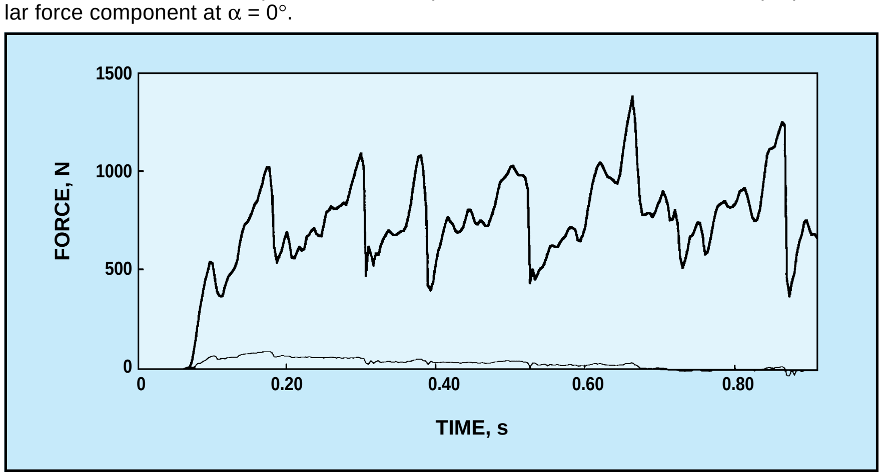
Experimental

Equipment

Trials were performed in a hydraulic materials testing system (MTS). The arrangement is shown schematically in **Fig. 1**. The wooden board was fixed by a press plate, and the cutting angle ε was 32° and the side angle was 0°. The knife was pressed through the wood at a constant speed of 75 mm/s, and the resistance of the wood was measured in two dimensions with three load cells. The forces acting on each load cell were recorded simultaneously 300 times per second.

After being cut, the chips were dried to a moisture content of about

3. The thick line shows the parallel force component and the thin line shows the perpendicular force component at α = 0°.



I. Intervals and transformations of the variables studied

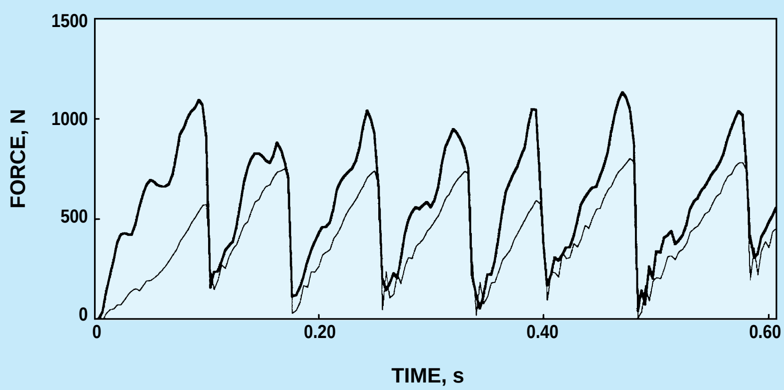
Variable	*-1 level*	*0 level*	*+1 level*
Chip length *l*, mm	15	25	35
Bevel angle ß´,	30	35	40
Clearance angle α,h°	0	3	6

II. Significant regression coefficients and their 95% confidence intervals, and coefficients of determination of the regression models

Response	*Constant*	*l*	α	*ß'*	α^2	$ß'^2$	*l*α	*lß'*	α*b'*	r^2
Force P	601 ±19	91 ±14	(2) ±15	93 ±13	41 ±24	_*	_	_	34 ±14	0.87
Log(SD(FP))	2.32 ±0.02	0.09 ±0.02	0.13 ±0.02	0.08 ±0.02	_	_	_	-0.03 ±0.02	_	0.84
Force N	223 ±36	37 ±15	163 ±28	39 ±24	-116 ±45	_	32 ±27	_	-40 ±27	0.77
Log(SD(FN))	2.04 ±0.12	(0.03) ±0.07	0.27 ±0.07	±0.08 ±0.06	_	-0.13 ±0.13	0.10 ±0.07	_	-0.13 ±0.07	0.60
Rel. Thick.	0.184 ±0.004	-0.022 ±0.005	-0.022 0.008	(-0.002) ±0.005	_	_	0.005 ±0.005	0.008 ±0.005	_	0.63

*Insignificant term.

4. The thick line shows the parallel force component and the thin line shows the perpendicular force component at α = 6°.



9%, and their lengths and thicknesses were measured with a sliding caliper.

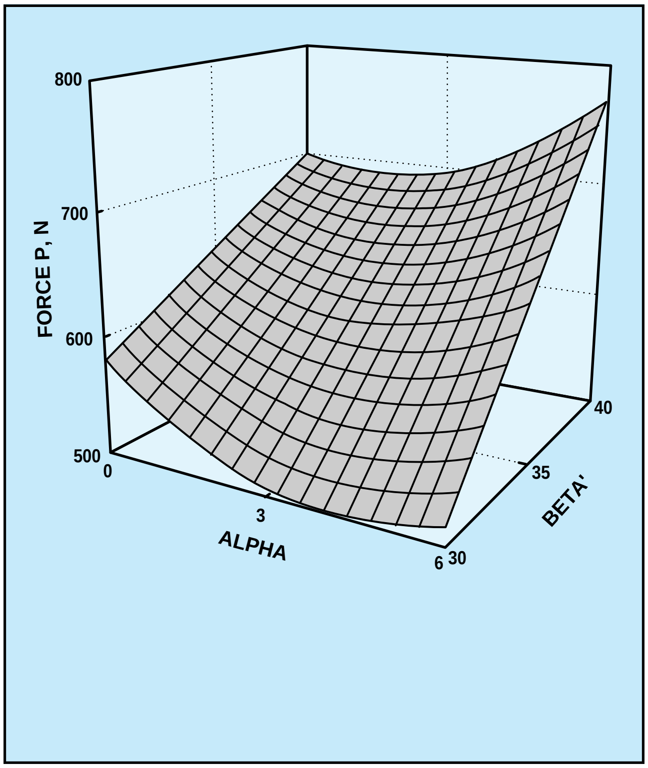
Some experiments were high-speed filmed with a video camera (500 frames per second) in order to study the fracture mode and conditions of contact between knife and wood.

Materials

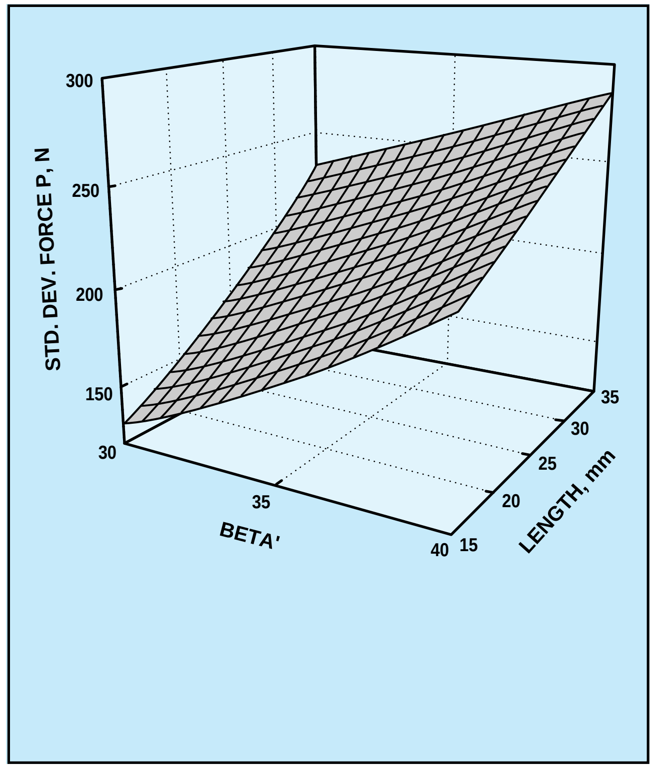
The knives were made of a commercial steel (0.9% C, 1.2% Mn, 0.5% Cr, 0.5% W, 0.1% V) hardened to 60 Rockwell C. The knife angle was 30° and the radius of the knife edge was approximately 10 μm, measured with a scanning electron microscope on imprints of the knives in a resin.

The wood used was sapwood of Norwegian spruce *(Picea abies)* from central Sweden. Two boards of knot-free, straight-grained and never-dried wood were prepared. They had similar densities (390 kg/m^3 and 394 kg/m^3 based on dry weight and wet volume) and moisture contents (20% and 19% based on dry weight). The length of the boards in the grain di-

5. The mean value of the parallel force component versus the clearance angle α and the bevel angle ß´ at a chip length of 25 mm



6. The standard deviation of the parallel force component versus bevel angle ß´ and chip length at α = 3°.



rection of the wood was approximately 1.5 m, the width in the tangential direction of the wood was 20 mm (± 0.2 mm) and the height in the radial direction of the wood was 44 mm (± 1 mm).

Experimental design

In the trials, the chip length, bevel angle ß´ and clearance angle α, **Fig. 2**, were varied with a factorial design *(6)* at three levels according to **Table I**. Six replicate tests were performed in each experimental point, and some additional combinations were also chosen to permit separation of the curvatures in the response of the different variables. A total of 70 trials were performed in random order. The complete set of the trials is presented in Appendix I and in *(7)*.

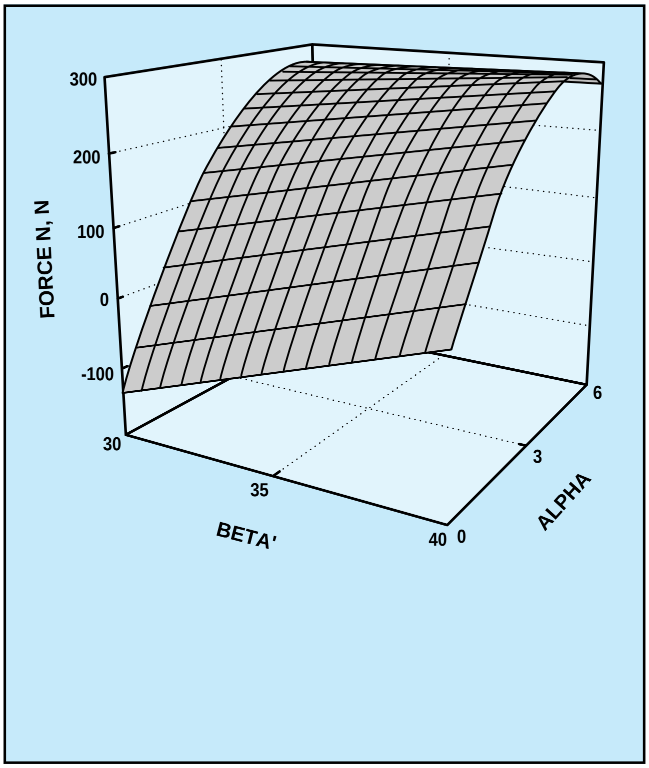
Results

As the knife penetrated into the wood, contact forces arose between knife and wood. The high-speed film revealed a zone of densified wood in front of the cutting side of the penetrating knife. The cutting force increased until a fracture was initiated, whereupon the force decreased. Sometimes the cracks started to grow close to the knife edge and sometimes they were initiated later, a few millimeters above the knife edge. When the fracture was initiated at a relatively small depth of penetration, the crack growth terminated after traveling only a short distance in the grain direction. When the crack growth was terminated, the cutting force increased as the knife continued to penetrate deeper into the wood. This continued until a fracture propagated all the way through the wood, thus forming a chip. In these trials, the cracks always propagated in the opening modus (modus I). Crack growth could occur under either stable conditions (i.e., more energy has to be supplied to maintain crack growth) or unstable conditions (i.e., the elastic energy built up in the system is greater than the fracture energy) for different chips formed in the same cut. In the film, no stick-slip behavior between knife and wood could be observed.

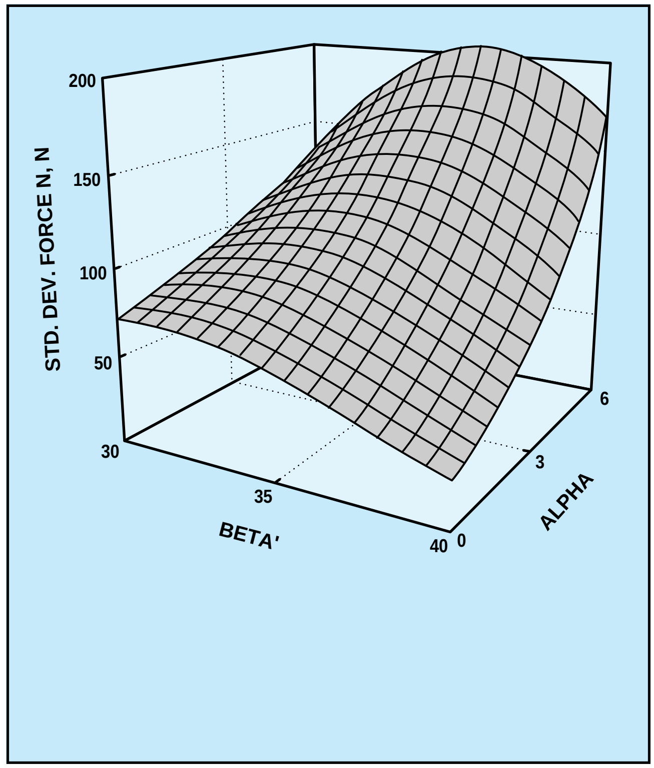
The resulting cutting force acting on the wood was divided into two components, one parallel (F_p) and one perpendicular (F_N) to the movement of the knife. The parallel component, which is directly related to the energy consumption, is defined as being positive in the direction of the movement of the knife, and the perpendicular force component is defined as being positive when acting away from the wooden board, i. e., to the left in Fig. 1.

Qualitatively, the cutting force was strongly dependent on the clearance angle. A characteristic example

7. The mean value of the perpendicular force component versus bevel angle ß´ and clearance angle α at a chip length of 25 mm



8. The standard deviation of the perpendicular force component versus bevel angle ß´ and clearance angle α at a chip length of 25 mm



of the force components when the clearance angle was 0° is presented in **Fig. 3**. The parallel component first increased and then decreased quickly after crack initiation, but still remained at a relatively high value. The perpendicular force component was close to zero throughout.

Force diagrams from cuts with a clearance angle α = 6° differed considerably from this pattern, **Fig. 4.** Here the perpendicular component was almost as high as the parallel component. The parallel force component also changed somewhat; here it dropped almost to zero each time a crack propagated all the way through the wood.

Since the force diagrams differed greatly, regression models were obtained not only for the mean values of the force components, but also for the standard deviations of the force components in each cut. The standard deviations were not symmetrically distributed, but the logarithmic values gave an approximately Gaussian distribution. A regression model of the chip thickness:length ratio was also obtained. The significant coefficients and their 95% confidence intervals as well as the coefficients of determination of all the regression models are presented in **Table II**. The values of the variables were transformed, i.e., they were all converted to –1 at the low level, 0 at the intermediate level and +1 at the high level according to Table I. In this way, the regression coefficients are independent of the units chosen, and this makes comparison between the effect of different variables easier. When the models in Table II are used, the variables are scaled according to Table I. **Figures 5 through 9** are based on these regression models.

The parallel force component F_P was mostly influenced by the chip length and the bevel angle, Table II. In Fig. 5, the mean value of the parallel force component F_P is shown versus the clearance angle α and the bevel angle ß´ at a chip length of 25 mm. A minimum at an intermediate level of the clearance angle was observed. The influence of the bevel angle was greater at large values of the clearance angle.

The variation in the parallel force component in each cut increased as the clearance angle increased, Table II. The standard deviation also increased when the chip length and bevel angle ß´ increased, Fig. 6.

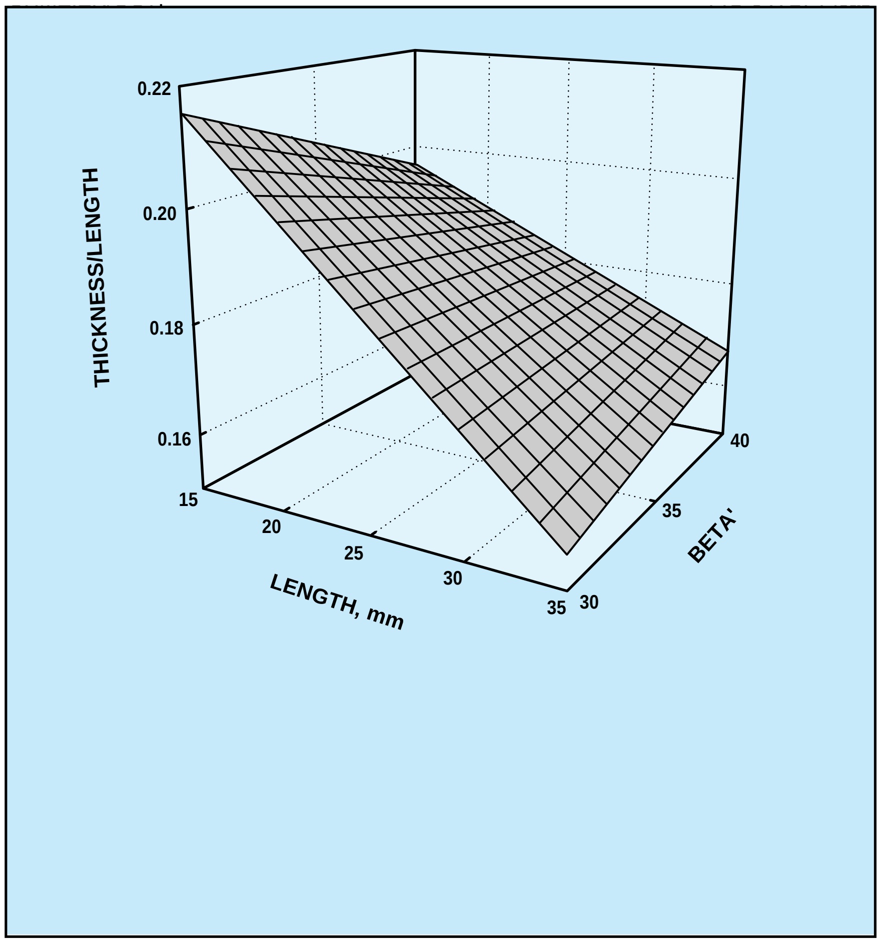
The influence of the clearance angle α and the bevel angle ß´ on the mean value of the perpendicular force component at a chip length of 25 mm is presented in Fig. 7. It shows that the clearance angle had a strong influence on the perpendicular force component, and that an increase in the bevel angle at low values of the clearance angle led to an increase in the perpendicular force component.

The influence of the clearance angle α and the bevel angle ß´ on the standard deviation of the perpendicular force component in each cut at a chip length of 25 mm is illustrated in Fig. 8. It can be seen that the clearance angle had a great influence on the variation in the perpendicular force component, especially at high values of the bevel angle.

Figure 9 illustrates how the chip thickness:length ratio depended on chip length and bevel angle ß´ when α = 3°. It shows that the relative chip thickness decreased with increasing chip length. At a short chip length, an increase in bevel angle gave rise to a thinner chip, but the effect was the opposite at a long chip length.

In each cut, wood chips with the same length were formed, but the chips had different thicknesses. This variation in chip thickness was not influenced by the variables in this experiment. The average variation in chip thickness was 22%, and this variation was dependent on the variability of the wood alone.

9. The relative chip thickness versus chip length and bevel angle ß´ at α = 3°.



Discussion

The experiments revealed that chip formation is a complicated process, since the variables interacted in an unexpected manner. This leads to the conclusion that a factorial experimental design is necessary when studying wood chipping, since the response to a change in one variable depends on the values of the other variables. Consequently, if this investigation had been performed at, e.g., another cutting speed or with another wood raw material, the measured responses could differ from those presented here. This should be borne in mind when interpreting the results of any investigation.

Other major discoveries were that the perpendicular force component could be quite large, and that the clearance angle had a great influence on the resulting cutting force, which has not been previously recognized.

A variation in the clearance angle affects not only the contact forces on the clearance side of the knife but also those on the cutting side of the knife. In order to study how the contact forces on the clearance side of the knife alone are affected by the clearance angle, the knife angle must also be changed when the clearance angle is varied, so that the "effective knife angle" α + ß and the contact forces on the cutting side of the knife are constant *(8)*. This has not been done when studying wood chipping, but it has been studied in the cutting of MDF, i.e., medium density fiberboard *(9)*. That investigation showed a significant change in the cutting force when the clearance angle was varied between 5° and 15°. However, in wood chipping the knife angle is normally relatively small, 30° to 35°, and the knife edge is consequently quite fragile. Therefore, in practice, the knife angle is made relatively small to decrease the cutting force, chip damage, and chip thickness, while still being large enough to maintain acceptable durability, regardless of the choice of clearance angle. In practice, the choice of clearance angle thus affects the contact forces on both sides of the knife. On the one hand, the clearance angle should be chosen large enough to create sufficient suction feeding of the logs but, on the other hand, rather small in order not to increase the effective knife angle more than necessary.

In this investigation, the mean value of the parallel force component was a minimum at the intermediate level of the clearance angle, Fig. 5. At larger angles, it seemed that the contact forces on the cutting side of the knife increased faster than those on the clearance side de-

Appendix I. Original data

Exp.no.	*l*, *mm*	*α*, *°*	*ß'*, *°*	$F_{p'}$, *N*	$F_{N'}$, *N*	*t/l*	$SDF_{P'}$, *N*	$SDF_{N'}$, *N*	*SDt/t*
1	36	6	30	645	368	0.195	331	252	0.155
2	14	0	30	415	4	0.226	82	29	0.285
3	15	6	30	390	208	0.230	157	127	0.193
4	26	3	35	570	340	0.184	182	128	0.234
5	34	0	30	678	-207	0.175	180	26	0.225
6	37	6	40	864	436	0.166	270	411	0.170
7	24	3	35	553	283	0.179	188	137	0.264
8	35	6	30	533	345	0.144	261	215	0.293
9	12	0	30	455	-180	0.246	66	134	0.319
10	15	6	30	396	214	0.201	162	125	0.208
11	25	3	35	573	286	0.186	207	128	0.313
12	33	0	30	654	-212	0.164	184	119	0.163
13	18	6	40	764	323	0.226	386	223	0.172
14	12	0	40	590	64	0.211	185	26	0.193
15	25	3	35	590	190	0.193	299	133	0.230
16	36	6	40	900	383	0.177	527	245	0.108
17	24	3	35	650	314	0.204	223	148	0.136
18	35	0	40	791	70	0.174	258	17	0.108
19	37	6	30	597	306	0.174	322	221	0.252
20	13	0	30	482	-207	0.219	116	145	0.313
21	16	6	30	387	200	0.185	154	119	0.218
22	25	3	35	532	294	0.154	204	146	0.303
23	35	0	30	684	-185	0.147	197	113	0.243
24	18	6	40	726	275	0.175	396	203	0.179
25	14	0	40	562	32	0.212	174	27	0.254
26	25	3	35	564	296	0.164	223	145	0.274
27	35	0	40	767	68	0.135	225	27	0.251
28	35	6	30	681	450	0.174	279	221	0.238
29	11	0	30	511	-258	0.258	97	141	0.201
30	15	6	30	548	325	0.201	234	189	0.270
31	22	3	35	679	393	0.177	242	164	0.232
32	30	0	30	704	-208	0.156	161	132	0.255
33	17	6	40	707	331	0.188	347	222	0.233
34	13	0	40	576	17	0.185	139	41	0.236
35	24	3	35	608	341	0.211	212	147	0.223
36	32	0	40	770	-5	0.178	164	52	0.146
37	38	6	40	830	455	0.156	414	259	0.262
38	22	3	40	679	394	0.169	249	173	0.201
39	24	3	30	490	302	0.166	198	161	0.202
40	25	3	30	462	322	0.177	151	126	0.230
41	35	6	30	601	432	0.148	286	253	0.370
42	14	0	30	429	-117	0.226	91	200	0.190
43	19	6	30	442	105	0.194	178	64	0.198
44	25	3	35	563	132	0.179	192	60	0.243
45	35	0	30	637	-20	0.153	177	39	0.264
46	15	6	40	580	107	0.195	280	69	0.280
47	15	0	40	579	-40	0.184	133	38	0.187
48	25	3	35	556	125	0.178	170	58	0.190
49	34	0	40	768	28	0.179	190	26	0.257
50	35	6	40	795	184	0.191	366	114	0.153
51	24	3	40	647	156	0.179	215	64	0.242
52	23	3	40	675	148	0.192	317	65	0.165
53	25	3	30	473	103	0.187	178	47	0.130
54	25	3	30	485	121	0.186	160	58	0.214
55	35	6	30	633	172	0.135	285	104	0.229
56	15	0	30	511	-67	0.233	84	47	0.164
57	16	6	30	470	113	0.217	182	63	0.218
58	24	3	35	631	132	0.209	220	76	0.271
59	34	0	30	669	-51	0.155	152	48	0.202
60	15	6	40	654	127	0.186	294	67	0.187
61	15	0	40	668	30	0.218	102	14	0.252
62	25	3	35	624	144	0.192	199	58	0.170
63	34	0	40	785	29	0.171	217	18	0.183
64	34	6	40	964	227	0.146	398	128	0.242
65	22	3	40	765	151	0.158	254	69	0.223
66	23	3	30	535	124	0.203	213	66	0.224
67	24	3	30	525	135	0.178	168	50	0.210
68	24	3	40	701	146	0.188	237	73	0.227
69	24	3	40	724	184	0.203	196	63	0.200
70	24	3	30	487	123	0.164	166	56	0.274

creased. In industrial chipping, the optimum clearance angle is probably somewhat larger than in this study, due to the suction feeding of the logs.

The clearance angle had a great effect on the resulting cutting force, which can be derived from the two force components by simple trigonometry. The mean and the standard deviation of the perpendicular component were influenced greatly by the clearance angle (Figs. 3, 4, 7, and 8). The mean of the parallel component was moderately influenced by the clearance angle (Figs. 3–5) but the standard deviation of the parallel component was influenced to a great extent (Figs. 3 and 4, Table II). The peak forces are approximately two standard deviations greater than the mean forces.

In these experiments, the energy required to cut the chips was approximately 2.3 MJ/m^3 solid wood at the intermediate level of the variables, which is somewhat lower than the values given by Kivimaa and Murto *(2)* and Buchanan and Duchnicki *(4)*, who reported values between 3 and 4 MJ/m^3 under reasonably similar conditions. This difference may depend on the difference in cutting speed, which in this range affects the friction a great deal *(10)*, and on differences in the wood material. Even though the cutting force increased with increasing chip length, the energy demand per cubic meter of wood decreased.

The energy demand was much affected by the bevel angle; it increased by about 37% as the bevel angle was changed from 30° to 40° at a chip length of 25 mm. This was definitely surprising, especially considering that neither chip thickness nor fracture mode changed. However, Kivimaa and Murto *(2)* observed that the sharpness of the knife greatly affects the energy demand in low-speed laboratory chipping but not in industrial chipping. Hence, a change in the bevel might not increase the energy demand as much as 37% in industrial chipping. As previously mentioned, the bevel increases the durability of the edge, and this should give a lower dust content in the chipping operation.

In the regression model for the variation of the perpendicular force component, the coefficient of determination was rather low ($r^2 = 0.60$). A likely explanation is that the knife holder was less stiff in this direction than in the other, yielding more noise in the measurements. It is also possible that local variations in wood properties yield more noise in this response. These variations in wood properties might also be the explanation of the relatively low coefficient of determination ($r^2 = 0.63$) of the regression model for the chip thickness:length ratio.

According to Kivimaa and Murto *(2)*, the chip thickness increases linearly with increasing chip length below a chip length of 40 mm. In the present study, the chip thickness increased less than proportional between 15- and 35-mm chip length, which is advantageous when a long but relatively thin chip is desired.

Conclusions

Wood chipping is a complicated process which depends on many factors, and great precautions should be taken before the results from any investigation are generalized. In this experiment on low-speed chipping, some noticeable effects were discovered:

- The force component perpendicular to the movement of the knife could be quite high.
- The clearance angle had a large influence on the resulting cutting force.
- A factorial experimental design was needed since several variables interacted. TJ

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