Cutting-forces when up-milling in beech

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Abstract

By use of a load cell, a computer and a fast scanning device we have examined the cutting-forces on the tool in a milling machine. Several experiments have been elaborated with different rotation and feeding speeds. The aim of the study has been to study, in detail, how wood chips are produced. By a better understanding of this process it must be possible to manufacture wooden details for furniture and other products with less errors and, hence, there will be less need for sanding and other expensive extra treatment in order to achieve an acceptable result of the finished surface. The load cell was used to register the forces in three directions. These registrations, however, were not easy to interpret because of the vibrations which were introduced in the experimental setup when milling started. A computerized filter therefore had to be used in order extract only those registrations which were of interest. We found that the cutting forces in beach varied from approximately 40 up to 86 N/cm in the work-piece feed direction, i.e. Y, and from about 14 to 51 N/cm in the X-direction, i.e. in the normal to the cut surface. A larger average chip thickness resulted in larger forces but we could not find a clear relationship which in full explained our result.

Introduction

Industrial equipment for planing and milling in wood has been in use for more than a century. There has also been of interest to study exactly how a wooden chip is produced in terms of forces on both the tool and the wooden detail. This in order to construct better machinery for this activity. There are a number of papers and reports where such measurements are reported and according to [1], page 517, the work seems to have started around 1930. These papers seem to mostly have dealt with so called orthogonal cutting, i.e. where the tool only moved in one direction in the wooden piece. At least one of the papers, [2] and also some later studies, such as [3] and [4] deal with peripheral cutting, where knives are clamped to the periphery of a cylinder, as found in normal milling machines. In [4] and [5] milling in metals was emphasized but the kinetics of the cutter-head and the tools are the same as for machining in wood. In spite of these early studies problems to be examined still exist and some recent papers are e.g. [6], [7] and [8].

In the last reference we have started to describe our own findings. The procedure for monitoring the forces on the tool can be found in that paper and we will only describe some vital things here in order to clarify the situation for new readers. We have also found a dissertation dealing with this interesting subject, [9].

A transducer, or a load cell, has been clamped to the table of a milling machine. On top of the cell the work-piece is mounted, see Figure 1, showing an experiment in pine wood. The milling now takes place on the edge of the

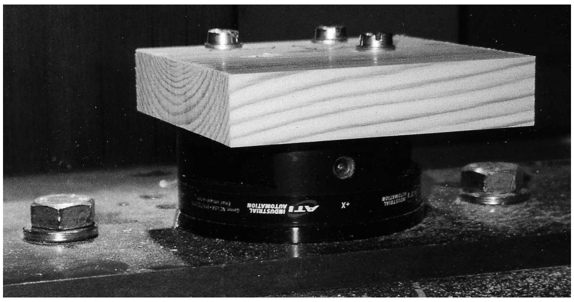

Figure 1: The load-cell, marked ATI, and work-piece setup in the milling machine. Photo by Jan Palmqvist.

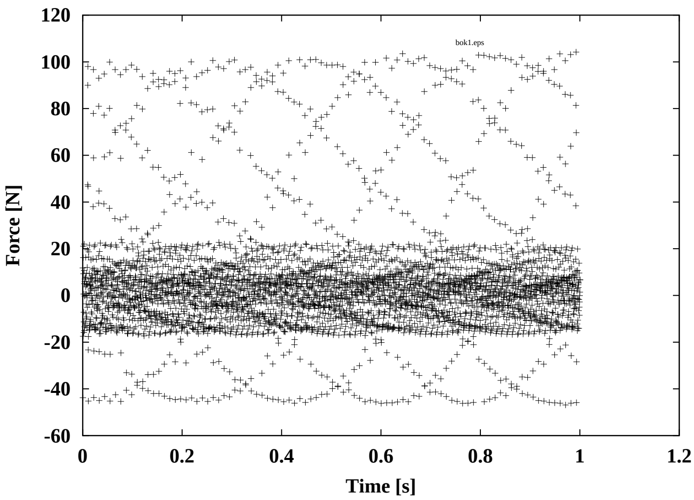

Figure 2: Readings from the load cell when milling in beech. No filter applied.

work-piece. It shall be noted that the cutting tool is the part that actually moves. The work-piece is always in the same position.

The load cell is coupled to a special monitoring card in an ordinary PC-computer. This card can be reached and addressed by a computer program written in the computer language C. Inside the load cell, special strain gauge meters are located and the card has to scan these meters very fast in order to get a number of readings during the very short time when a wooden chip is produced. The faster scanning process the more readings can be achieved. In our setup the total scanning process lasts only one second but with a speed of 4000 Hz. Only 0.00025 s pass between two readings of the transducer. Because of the rotating cutter-head the tool will only be cutting something for a very short moment which length in seconds depends on the revolution speed of the cylinder where the tool is clamped. In order to minimize the problems with different geometries, sharpness etc. between different tools, our cutter cylinder was only equipped with one such tool, or knife. Most of our readings were therefore registered when the tool only were in transport between two cutting operations. In Figure 2 an experiment in beech wood is shown.

From Figure 2 it is obvious that the forces vary from about - 50 to about 100 N but most of the readings show values between - 20 to + 20 N. The forces shown, act in the Y direction i.e. the same as the feeding of the wooden piece. In this case the cutter head knives rotates in the opposite direction to the work-piece feeding, so called up-milling was used. Because of this there should be only positive values in the files and we have therefore to dig into the actual data file in order to reveal what happened.

In [8] it is shown that one possible way to act is to first identify values that clearly emanate from cutting operations. Such parts of the data file must show increasing values because the chip grows larger and larger. All of a sudden the cutting stops, i.e. when the knife leaves the work-piece surface, and hence, a very low value should be registered. In this first data file such a pattern can be identified for readings no. 38-43, see Table 1.

Number	Time [s]	X	Y	Z
37	0.00925	3	-51	-33
38	0.00950	-104	48	-69
39	0.00975	-213	195	-67
40	0.01000	-206	474	-58
41	0.01025	-58	900	27
42	0.01050	111	980	135
43	0.01075	103	467	164
44	0.01100	-11	-233	33

Table 1: Values from the data file as registered from the load cell.

The scanning card sends integer values to the computer. A value of 100 corresponds to 10 N. The maximum force in Table 1 is 98 N. The thickness of the work piece was 19 mm and hence a force of 51 N/cm was experienced. In [2] birch is examined and the forces shown to be less than 8 kg/cm which nowadays equals 80 N/cm. Our measurements seems therefore to be of the right magnitude.

We must now find the other moments when cutting occured in our data set. The same pattern was observed for starting points at reading no. 82, 126, 169 and so on. Therefore, it was possible to calculate the rotating speed in the actual experiment. The load cell is scanned each 0.00025 s and hence it takes 0.011 s between each cutting operation. This corresponds to a revolution speed of 90.9 r/s or 5,454 r/m. The aimed speed, set in the machine, was 5,000 r/m but a slightly higher rotation was therefore achieved. In [8] we created another computer program, written in C under LINUX, and by use of that it was possible to automatically identify almost all the occasions when cutting occurred. This happened 112 times during the examined second, see Figure 3.

It is obvious that the maximum forces during each cutting operation were about 100 N and an average value of the 112 values was calculated to 84.6 N or 45 N/cm. It must be noted here that because of the scanning process it was not always possible to find the maximum force during each cut but instead only the maximum among those that were registered. This explains why the average value is so much lower than the maximum of all registered values, which was 104.2 N. If Figure 3 is studied in more detail it is obvious that the C-program

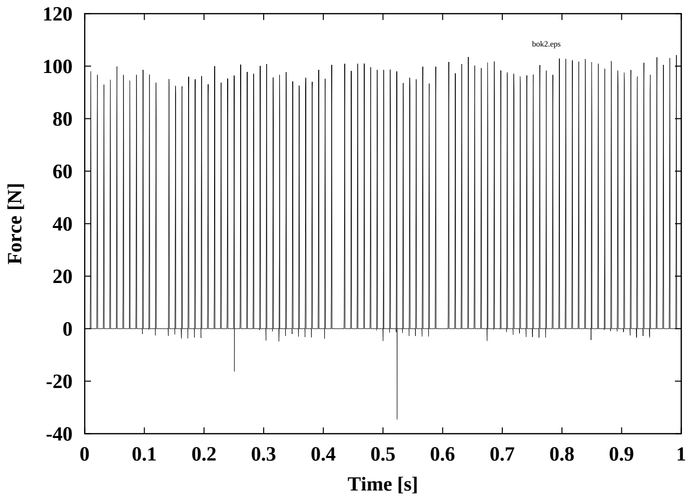

Figure 3: Readings from the load cell when milling in beech. Filter applied.

was not able to detect the precise cuttings and some misinterpreting occurred. Only about 90 peaks should be present in Figure 3 according to the revolution speed calculated above. Also, not all of negative values were deleted.

Forces in the X- and Y-directions

It was shown already in [2] that forces occur in two directions, one called "Hauptschnittkraft" which was called the cutting force in [1], and one called "Stoßkraft" or impact force. In [9] the terminology is a little different, "Vorschubskraft" and "Normalkraft". The first type corresponds to our Y-direction while the other one is present in the X-direction. The load cell is able to detect forces in three directions and some rotations as well. In [8] it was shown that forces were of interest in two, i.e. the X- and Y-directions, while the Z-direction should have zero values. The author to [9] shows, however that this so called "Passivkraft" has a small, but still, measurable value. The X-direction in our case was perpendicular to the feeding of the work-piece and those forces act in the direction of the normal to the cutting plane, cf. the German terminology. Note that we cut the work-piece on the edge. A number of experiments were now elaborated with different setups of the feeding speed, knife orientation and so forth.

Rake angle of zero degrees

In the studied case above milling with a hook, or rake, angle of 0° was used, see Figure 4. Four experiments with the same speed and rake angle setup were elaborated. However, the average chip thickness, δ_m, was varied, and the registered maximum forces for the other four sets of values were 104.2, 137.3, 143.1 and 152.9 N for δ_m of 0.03, 0.05, 0.07 and 0.09 mm respectively. We decided to do so because, according to [2], the value of δ_m influences the cutting force in a significant way and our own measurements also showed that this was the case. Each chip produced has a sickle-like shape and therefore it was

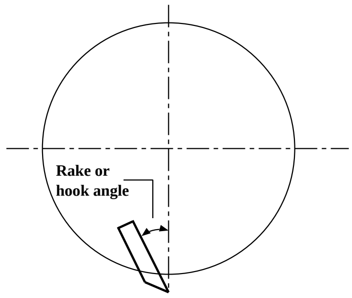

Figure 4: Rake or hook angle for a cutter knife.

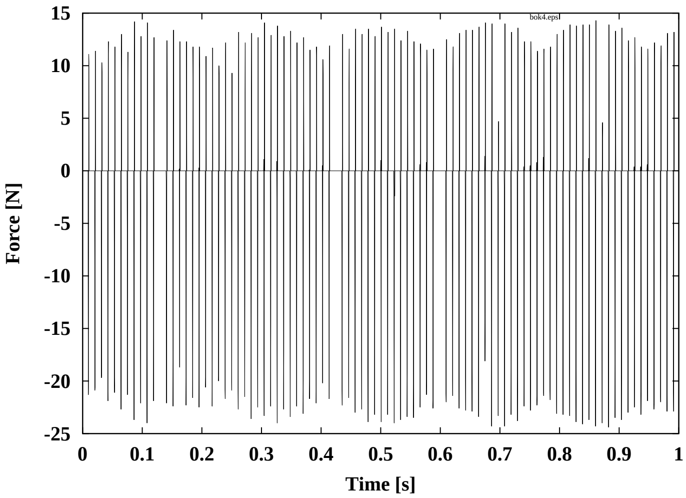

Figure 5: Forces in the X-direction. Rake angle zero degrees. $\delta_m = 0.03$ mm

necessary to calculate an average thickness. In [1], p. 518, it is shown that this value, δ_m, can be calculated as:

$$\delta_m = e\frac{t}{D};\ where\ e = \frac{f}{ni}$$

t shows the depth of the cut, D the diameter of the cutter, f the feed speed, n the revolution speed and i the number of cutting edges.

The forces in the X-direction have a much lower magnitude. In [8] it was shown that they are about ten times lower than those in the Y ditto. The result from the $\delta_m = 0.03$ mm data file is shown in Figure 5. It is obvious from Figure 5 that a more complicated pattern occurs when the X-direction is studied. The forces have a maximum value of about 25 N, or approximately 13 N/cm, on the negative side in the graph. The positive values are somewhat smaller, about 13 N or approximately 7 N/cm. In [8] we tried to analyze why these forces showed such a behavior, but unfortunately, a satisfactory solution was not achieved. A study was also performed in [9] where it was shown that the knife edge probably pushes on the work piece before cutting actually occurs. Unfortunately, he did not mention that the force changes sign during the incision but this might be

δ_m	X-dir.	Y-dir.
0.03	26.1	85.5
0.05	27.1	104.0
0.07	30.3	130.4
0.09	-40.8	131.1
0.11	-76.3	147.7
0.13	-75.8	141.4
0.15	-45.6	117.0
0.17	-49.9	115.0
0.19	39.8	113.3
0.21	-61.1	122.2
0.23	-61.5	128.3
0.25	50.9	126.4
0.27	65.6	142.2
0.29	-68.1	165.5

Table 2: Maximum cutting forces [N] for X- and Y-directions for different δ_m, rake angle 10°.

the effect of a relatively slower monitoring equipment.

In our experiment a higher δ_m, e.g. 0.11 mm resulted in X-forces of up to 120 N. Unfortunately, the experiment had to be interrupted because the experimental setup was set into severe vibration, probably because of the zero degree rake angle. Therfore, a further increase of δ_m would probably have had hazardous effects on the surroundings.

Rake angle of 10 degrees

When the knife was set in a 10° rake angle it started to cut in a more normal way. A full study could, therefore, be elaborated. The average chip thickness was therefore varied between 0.03 mm to 0.29 mm, in 14 steps. In fact, it is the feeding speed of the work piece, f that has been changed because the higher this speed the larger becomes δ_m, *vide supra*. The result is shown in Table 2. According to [2] the cutting forces should grow when the average chip thickness grows. Such a behavior is not obvious in Table 2. We have also checked if our filter malfunctioned for the data files where δ_m was 0.15 - 0.19 mm but found no such evidence. For 0.15 mm the largest registered force in the Y-direction was 124.6 N while they were 115.1 and 117.1 for 0.17 and 0.19 mm respectively. The computer filter therefore seems to have worked in a sufficient way. There might also be an error e.g. in the last data set showing a force of 165.5 N. The resulting file from the filter is therefore shown in Figure 6. In Figure 6 it is obvious that the filter did not recognize any cutting in the beginning of the scanning sequence. This might be a result of setting the trigging Y-direction value too high, in this case 60.0 N. If such a value is not present in the data file no values are transfered to the output file. This is what have happened in the first part of the process, no cutting was detected. In the latter part of the graph such output is present but it seems that too many values are sent to the file. In spite of these calamities it is clear that large values of up to 165 N was

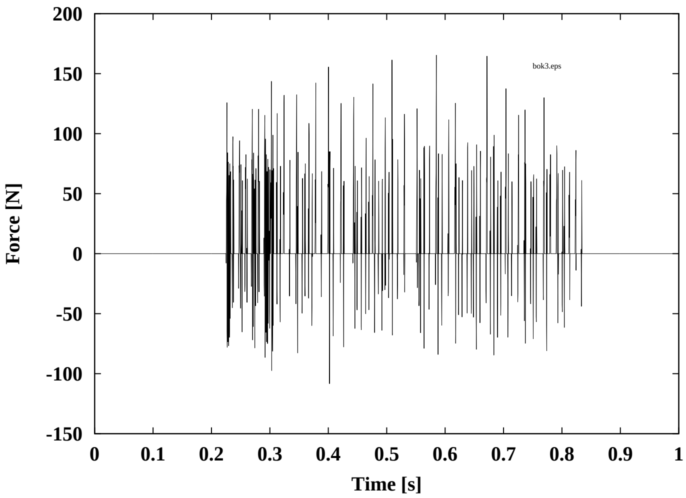

Figure 6: Forces in Y-direction for a large average chip thickness.

present during the observed second.

The X-values are also somewhat confusing, see Table 2. We have shown the largest value found, negative or positive, by the filter. It is obvious that the X-forces grow larger when the average δ_ms increase, but we also find large values in the middle of Table 2.

Rake angle of 20 degrees

The same experimental setup was used for a 20° rake angle. Table 3 shows the result.

Also here we see that the smallest absolute value in the X-direction is found for the smallest δ_m while the largest X-force is detected for the highest average chip thickness. In the Y-direction the same pattern occurs for the smallest δ_m but the largest force was found in the middle of the data set.

A closer study of the data sets

It is now possible to elaborate a graph where it is shown how the maximum absolute forces depends on the average chip thickness, see Figure 7. In [2] it is stated that the cutting forces depend on the average chip thickness and that an almost linear relationship is present. Our findings, however, do not show such a linear behavior. It is therefore necessary to study the data files in more detail in order to find out what happened.

In Table 3 it is shown that the maximum force in the X-direction changed sign between an average chip thickness of 0.03 mm, i.e. 19.3 N, and 0.05 mm, i.e. -28.4 N. Firstly, we must identify when a chip was produced. The revolution speed was set to 5000 rpm, or 83 rps. One revolution therefore should take 0.0012 s and a chip must therefore have been produced during the first, say 50 values in the data file. Our cutting depth was set to 2 mm and the diameter of

δ_m	X-dir.	Y-dir.
0.03	19.3	76.0
0.05	-28.4	103.2
0.07	-35.4	122.9
0.09	45.3	87.3
0.11	42.5	105.7
0.13	26.6	124.3
0.15	35.9	110.0
0.17	29.1	97.7
0.19	49.1	79.8
0.21	49.8	87.3
0.23	38.1	87.3
0.25	38.4	91.9
0.27	54.4	96.4
0.29	95.2	113.3

Table 3: Maximum cutting forces [N] for X- and Y-directions for different δ_m, rake angle 20°.

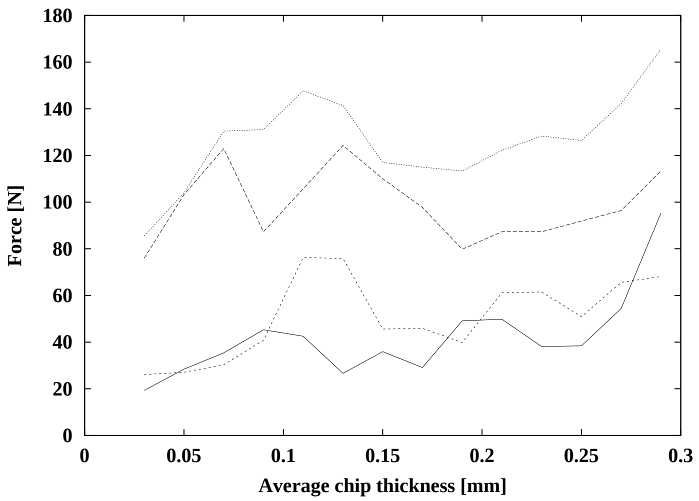

Figure 7: Forces in X and Y-directions for varying average chip thickness.

Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.
348	-40	-166	390	-20	-272	436	9	-156
349	18	-184	391	-76	151	437	-51	85
350	-37	119	392	-68	425	438	-113	441
351	-89	493	393	-26	328	439	-58	549
352	-31	545	394	51	63	440	80	207
353	127	-361	395	148	-36	441	136	-290
354	1	-436	396	76	151	442	31	-428
355	-133	-57	397	-79	414	443	-106	-111

Table 4: Values from the load cell in X- and Y-directions for a rake angle of 20 degrees. $\delta_m = 0.03$ mm

the tool was 60 mm. From trigonometry it is found, see e.g. [8], that:

$$0.002 = 0.03 - 0.03 \times cos\varphi$$

and hence φ will equal 21 ° or 0.367 rad. The revolution speed tells us that 2π rad takes 0.012 s and hence 0.367 correspond to 0.0007 s. The scanning occurs each 0.00025 s so there should be only three registrations during each incision.

During the 50 first registrations none of those came up to 60 N which was set in the filter. On the other hand, when the total data set was examined about 25 such events occurred. It was noted that 87 lines in the data set were present between such registrations, while 42 lines differed in about 5 cases. It was therefore assumed that every revolution of the cutter-head takes $43 \times 1/0.0025$ seconds which corresponds to 5,581 rpm. When the filter level was reduced to 50 N a larger number of events occurred but also "the noise" in the output. However, starting at line 352 about 13 consecutive incisions could be identified with this filter level. In Table 4 three such incisions are shown, note that only three values in each set actually were scanned during an incision.

In Table 4 it is found that line no. 352 shows a Y-direction force of 54.5 N and therefore this value is detected by the filter. The incision has probably already started because two lines earlier also a positive value occurred, 11.9 N. At line 353 the actual cutting has probably stopped because of the negative value of -36.1 N. It is hardly plausible that the Y-direction force can be negative when the knife is actually cutting. The force also seems to grow from the start of the cut but it becomes smaller again in the end of the incision. The force in the X-direction has a much smaller magnitude but at least sometimes it is evident that it goes from negative to positive values. The maximum Y-direction force occurred at line no. 3,186 in the data file which corresponds to 0.7965 s, and the series reads -57, 419, 760, 351, -376. The pattern is therefore the same also here. The forces in the Y-direction grow up to their maximum value and then decline. In the X-direction the readings are 149, 113, -39, -41, 135 respectively. When the Y-value 419 is registered the tool must be cutting and at the same moment the X-value was 113, or 11.3 N. The next two readings show negative values but it must be assumed that the knife still was cutting and, hence, the force have changed direction. Such a behavior was not found in 4.

The same examination was also elaborated for the data file corresponding to an average chip thickness of 0.05 mm but no pattern could be detected by the filter set to 60 N. When the data file was scrutinized it was found that the cutting forces in the Y-direction were larger and hence a higher filter level had to be set, 90 instead of 60 N. Now a pattern was discerned and such high

Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.
68	101	-404	110	143	-386	150	53	74
69	113	-1040	111	26	-479	151	25	-299
70	-25	-417	112	-136	-30	152	-21	-153
71	-201	604	113	-121	452	153	92	460
72	-124	906	114	52	517	154	120	1032
73	145	373	115	163	134	155	94	822
74	276	-367	116	90	-378	156	86	-274
75	101	-768	117	-76	-543	157	122	-1010

Table 5: Values from the load cell in X- and Y-directions for a rake angle of 20 degrees. $\delta_m = 0.05$ mm

Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.	Line no.	X-dir.	Y-dir.
14	-153	72	58	-162	120	101	-218	154
15	35	133	59	21	119	102	-20	115
16	254	573	60	260	500	103	301	457
17	138	646	61	153	629	104	212	631
18	-54	16	62	-59	105	105	-71	153
19	-24	-502	63	-36	-427	106	-76	-416
20	87	-254	64	95	-279	107	104	-313
21	42	259	65	59	198	108	98	186

Table 6: Values from the load cell in X- and Y-directions for a rake angle of 20 degrees. $\delta_m = 0.09$ mm

Y-levels occurred with an interval of about 87 lines in the file and the first one found for line 72. Because of the revolution speed high values should also be present around lines 115 and 158. These lines were examined and the result is present in Table 5. It is obvious that the level of the Y-forces are increased in a significant way between Tables 4 and 5. The X-value of -284, corresponding to a force of -28.4 N was found in lines 164, i.e. outside of the assumed incision, see Table 5, and in line 339 where the same conditions should be present. Also for the next level of δ_m, i.e. 0.07 mm, the forces were increased.

For the next level, i.e. $\delta_m = 0.09$ mm, the forces went down again which does not support the findings in [2]. We will therefore show some registrations also from that data file. Here, the original filter level of 60 N seemed to have worked very well. The first hit was found for line 17 and the next ones for lines 61 and 104, i.e. an interval of about 43 lines. In Table 6 the values for the input data file are shown. As is obvious from Table 6 the levels of the Y-forces are lower than the ones present in 5. Why this was so, is something still to be explained.

Conclusions

We have examined the cutting forces when up-milling in beech wood. By use of a load cell, which could be scanned 4000 times each second, a number of data were recorded by a computer. These data showed the forces on the load cell. According to findings about 50 years ago these forces should depend mostly of the average chip thickness. However, this phenomenon could not be identified in our 33 experiments where such data have been scrutinized. Each of the 33 data files contained 4000 lines with X- Y- and Z-forces and hence a computerized filter was used. Sometimes this filter malfunctioned but ocular inspection of some suspicious parts did not contradict these first results. In spite of the high scanning rate, only three readings from each incision were present in the data file. Fortunately, each file contains about 80 such incisions. It was, however, very difficult to study exactly how the forces varied when a chip was produced. More experiments with a much slower revolution speed of the cutter head must therefore be performed. Our experiments showed that the cutting forces in beech varied from about 40-86 N/cm in the work-piece feed direction while they were located in an interval of 14-51 N/cm perpendicular to that feeding.

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