# ANALYSIS OF CUTTING FORCES IN STRAIGHT-KNIFE PERIPHERAL CUTTING OF WOOD

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**Abstract:** Effects of rake angle, wavelength, and depth of cut on cutting forces during straight-knife peripheral milling of sugar maple were determined. Progressions of normal ($F_N$) and parallel ($F_P$) force components during a typical up-milling cycle were determined. Results showed that at the initial step of the cut, $F_N$ was negative, ie the knife edge pushed the workpiece downward. The part of the knife path that remained visible on the machined surface was always created in such a situation. As the knife edge advanced in the cutting path, $F_N$ increased, reached a maximum negative value, then decreased to 0 N/mm, turned positive, and continued upward. $F_P$ was always positive and increased as chip thickness increased. Positive $F_N$ and $F_P$ reached a maximum just prior to emergence of the knife from the workpiece at about the maximum thickness position. However, when chip splitting occurred, the maximum positive $F_N$ and $F_P$ occurred before that maximum thickness position was reached. Maximum negative $F_N$ and $F_P$ increased as rake angle decreased and as wavelength increased. Maximum positive $F_N$ increased as rake angle and wavelength increased. Maximum positive $F_N$ and $F_P$ were also affected by depth of cut but to a lesser degree. Impact of these maximum cutting forces on production of defects was analyzed, and ways to decrease them were discussed.

***Keywords:*** Cutting forces, peripheral cutting, up-milling, sugar maple.

## INTRODUCTION

In peripheral cutting, material is removed from the workpiece in the form of individual chips. These chips are formed by intermittent engagement of knives mounted on the periphery of a rotating cutterhead. The resultant surface consists of a series of individual waves produced by the successive engagement of each knife (Koch 1985). Peripheral up-milling is the most common process used for planing wood along the grain. At the beginning of an up-milling peripheral cutting cycle, the cut occurs essentially parallel to the wood grain, and chip thickness is minute. This condition favors the production of Franz type II chips, which fail in shear, tend to form continuous spirals, and are associated with good surface quality (Koch 1985; Hoadley 2000). This initial portion of the cutting path will remain visible on the new surface. As the knife movement progresses, chip thickness increases and attains its maximum value just before the knife leaves the workpiece. However, when the knife is close to leaving the cutting zone, the cut is done at a certain angle to the grain. As a result, at the end of the cutting cycle, a Franz type I chip, which is formed by

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splitting ahead of the tool, is often produced (Koch 1985; Hoadley 2000).

The resultant force applied by the tool on the workpiece during the cut may be decomposed in a parallel ($F_P$) and a normal ($F_N$) component in relation to the surface produced (Fig 1). Magnitude and direction of these components depend on a number of factors related to the cutting tool, cutting conditions, and workpiece characteristics (Koch 1985). The normal cutting force component plays an important role on surface quality. In planing along the grain, normal forces can act downward, compress the superficial tissues, and might provoke cell crushing and raised grain (Fig 1) (River and Miniutti 1975; Stewart 1980; Stewart and Crist 1982). Detriments of crushing superficial tissues have been extensively explained in previous works (River and Miniutti 1975; Hernández and Naderi 2001; de Moura and Hernández 2006). In contrast, normal forces can also act upward and increase the risk of torn grain as well as distort and weaken the structure of superficial tissues (Fig 1) (Palmqvist and Johansson 1999; de Moura and Hernández 2006). Thus, the normal force component should be as low as possible. It is therefore very important to know how cutting conditions affect cutting forces.

Several studies have been done on forces generated in orthogonal cutting. Thus, effects of rake angle, cutting depth (Woodson and Koch 1970; Axelsson et al 1993), knife wear (Axelsson et al 1993; Hernández and de Moura 2002; Hernández and Rojas 2002) as well as wood density (Woodson and Koch 1970; Axelsson et al 1993), moisture content, and temperature (Axelsson et al 1993) have been studied. However, data on forces produced in peripheral cutting are still scarce, and additional methods should be developed to facilitate interpretation and comparison of results.

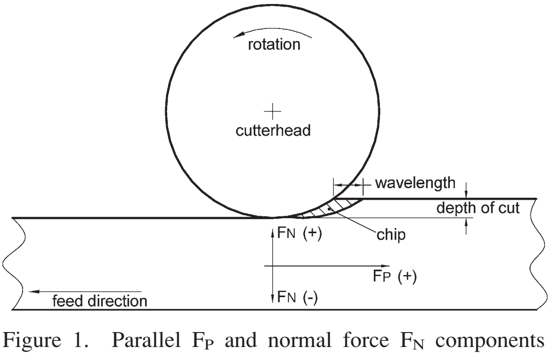


Figure 1. Parallel $F_P$ and normal force $F_N$ components during up-milling. Diagram shows that $F_N$ can act upward (positive value) or downward (negative value).

Palmqvist and Johansson (1999) presented a method for measuring forces during straight-knife peripheral cutting. Changes in force components during up-milling a single chip were described. These authors demonstrated that the parallel force increases gradually during the cut, whereas the normal force is downward at the beginning and becomes upward from the middle to the end of the cutting cycle. The normal force attains its highest upward value close to the end of the cutting cycle.

This study evaluated effect of rake angle, cutting depth, and wavelength on behavior of normal and parallel force components in peripheral straight-knife planing of sugar maple wood.

## MATERIALS AND METHODS

Sugar maple (*Acer saccharum* Marsh.) wood, a diffuse-porous hardwood commonly used for indoor applications, was selected for this study. Four air-dried flat-sawn samples were stored in a conditioning room at 20°C and 40% RH until they reached 8% equilibrium moisture content. After conditioning, samples were straight grain-oriented and cut to 150 mm long (L), 50 mm wide (T), and 19 mm thick (R). Average and standard deviation of basic density of the samples were 610 and 17 kg/m$^3$, respectively. Each sample underwent all cutting tests. Up-milling was performed with a straight-knife cutterhead that had 70 mm of cutting radius and was mounted on the horizontal shaft of a milling machine. Only one of the four knives on the cutterhead was set for cutting. The remaining knives served as counterbalance. High speed steel knives were freshly sharpened with three different geometries. Rake and knife angles of the knives were 10-50°, 20-40°, and 30-30°, respectively. Clearance angle was always 30°.

Roughness of the rake face of the knives, near the cutting edge, was measured with a Micromeasure confocal microscope. A surface of 40 $mm^2$ was analyzed per knife. Data were collected with Surface Map 2.4.13 software using an acquisition frequency of 300 Hz and a scanning rate of 3 mm/s. Average roughness ($S_a$) was determined using Mountain Software (Besancon, France) based on ISO (1997). A cutoff length of 0.25 mm combined with a Gaussian filter (ISO 1996) were used to calculate mean roughness ($S_a$) of the rake face for each knife used.

Samples were fed parallel to the grain at 0.625 m/min. Rotation speed of the cutterhead was set to obtain 15 and 27 knife marks per 25.4 mm of length. This corresponded to 1.75- and 0.93-mm wavelengths, respectively. Two cutting depths were also tested: 0.25 and 0.50 mm. Variables tested in the experiments are summarized in Table 1.

During machining, wood samples were fastened to a Kistler (Winterthour, Switzerland) 9257B quartz three-component dynamometer, which was fixed to the feeding table of the milling machine. Given this assembly, forces during peripheral milling were measured in relation to the feed direction and not in relation to the tool motion in the workpiece (as usually referred to when orthogonal cutting). A charge amplifier Kistler type 5010B equipped with a 180-kHz analog low-pass filter was used to amplify and condition input data. A short time constant (1 s) was chosen to allow measurement of the fast time-variant cutting forces. Normal ($F_N$) and parallel ($F_P$) components of the cutting force signals were digitized at a rate of 16,000 samples per second and stored into a PC disk memory for further analysis. Lateral force was considered negligible and not measured given that tests were performed with a straight-knife cutterhead. Ten successive knife cuts (or cutting cycles) for each pass and sample were examined. This corresponded to the analysis of 480 knife cuts for the entire experiment. All negative parallel forces as well as their corresponding normal forces were set to zero as proposed by Palmqvist and Johansson (1999). No additional filtering was performed on the original data. According to Palmqvist (2003), the pushing action of normal force was represented by negative values and the pulling action by positive values (Fig 1).

## RESULTS AND DISCUSSION

Typical progressions of normal, parallel, and resultant cutting forces during one cycle are shown in Fig 2. The theoretical undeformed chip shape and the instantaneous progression of the chip thickness are also represented. Chip shape, derived from the parametric equation of movement of the tool and workpiece as well as instantaneous chip thickness were calculated based on formulas described by Martellotti (1941).

At the initial step of the cut, $F_N$ was negative, ie the knife edge pushed the workpiece downward (Fig 2). For all cutting conditions studied, analyses of the knife cuts showed that the part of the knife path that remained visible on the machined surface was always created under such conditions. As the knife edge advanced in the cutting path, normal force increased, reached a maximum negative value, then decreased to 0 N/mm, turned positive, and continued upward. $F_P$ was always positive and increased as chip thickness

Table 1. Variables tested in the experiments and related cutting parameters.

| Variables | Values | | | |
|---|---|---|---|---|
| Rake angle (deg) | 10, 20, and 30 | | | |
| Wavelength (mm) | 0.93 | | 1.75 | |
| Depth of cut (mm) | 0.25 | 0.50 | 0.25 | 0.50 |
| Feed speed (m/min) | 0.625 | 0.625 | 0.625 | 0.625 |
| Cutting speed (m/s) | 4.95 | 4.95 | 2.62 | 2.62 |
| Length of a single cutting path (mm) | 5.93 | 8.39 | 5.94 | 8.40 |
| Average chip thickness (mm) | 0.039 | 0.055 | 0.074 | 0.104 |
| Maximum chip thickness (mm) | 0.066 | 0.098 | 0.104 | 0.165 |

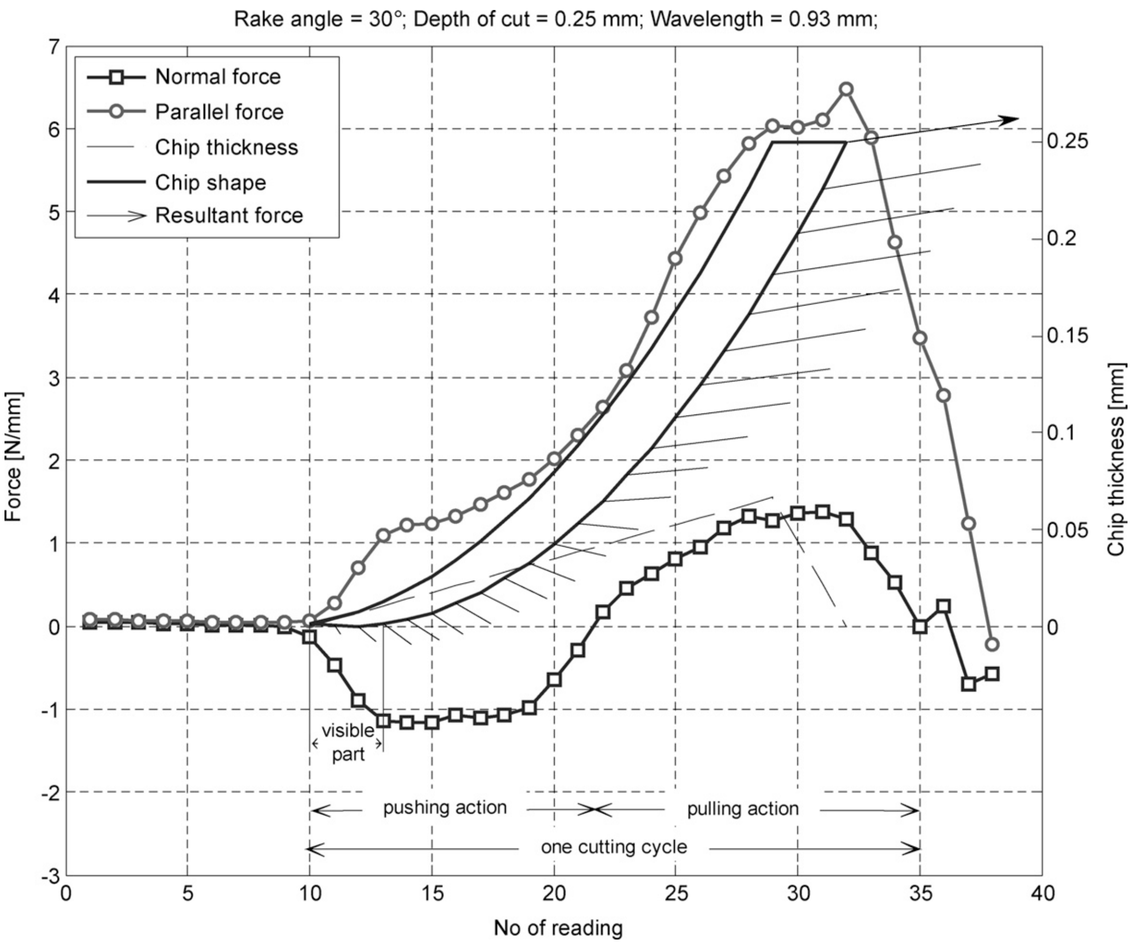


Figure 2. Progression of parallel and normal cutting forces during an individual chip length along with the theoretical chip shape and chip thickness. Resultant force is also represented by successive vectors.

increased. $F_N$ and $F_P$ should both reach a maximum just prior to emergence of the knife from the workpiece (at the maximum thickness position). However, Fig 2 shows that maximum positive $F_N$ and maximum $F_P$ components do not correspond exactly with maximum chip thickness. This slight offset could occur because the chip shape shown is theoretical (undeformed), and it is understood that the acting forces tend to stress and deform the workpiece body and the chip. In other cases, maximum $F_N$ and $F_P$ occurred before that maximum chip thickness was reached. This occurred when the $F_N$ component exceeded tensile strength perpendicular to the wood grain before the knife reached the theoretical maximum chip thickness position. As a result, a splitting phenomenon occurred, causing earlier release of the cutting force components.

A detailed analysis on the maximum force components reached during a complete cycle of cut was conducted. Because the normal force component changed from negative to positive during the cutting cycle, both maximum negative and positive forces were considered separately.

## Parallel Force Component

The contribution of the parallel component of the cutting forces to machined surface quality may appear less important compared with that associated with the normal component. However, the parallel force may be related to production of defects such as torn edges when the tool leaves the workpiece at the end of the milling operation (Palmqvist 2003). The magnitude of the parallel force, in particular its maximum, will affect the occurrence of this defect type. To determine the influence of independent variables on maximum parallel force, an n-way analysis of variance (ANOVA) was performed. The three independent variables (rake angle, wavelength, and depth of cut) and their two- and three-way interactions had a statistically significant effect on maximum parallel force (Table 2).

Within the range of cutting conditions studied, effect of rake angle on maximum $F_P$ was the highest, followed by wavelength, and finally by cutting depth. Maximum $F_P$ decreased almost linearly as rake angle increased (Fig 3). The highest value of maximum $F_P$ was obtained at the lowest rake angle (10°), highest wavelength (1.75 mm), and highest cutting depth (0.50 mm). However, the triple interaction analysis showed that the effect of rake angle on this force depended on wavelength and cutting depth variation. Thus, Fig 3 shows that effect of rake angle on maximum $F_P$ was more pronounced for the 1.75-mm wavelength than for the 0.93-mm wavelength. However, the effect of rake angle was greater for the 0.50-mm depth of cut than for the 0.25-mm depth of cut (although this effect is seen only for 10° of rake angle). Finally, effects of cutting depth and wavelength on parallel force decreased as rake angle increased. Thus, at 30° rake angle, the effect of depth of cut on $F_P$ was nil, whereas that of wavelength was still present.

From a practical point of view, it is obvious that a torn edge during machining should be avoided. This can be accomplished by using high rake angles and low wavelengths. Variation in cutting depth at higher rake angles would not have any effect on torn edge incidence. If rake angle is low, for instance 10°, torn edge occurrence can be controlled by

Table 2. Analysis of variance (rake angle, wavelength, depth of cut) for the maximum force components obtained during a peripheral up-milling knife cut of sugar maple wood.

| Source of variation | Degree of freedom | Maximum $F_P$ | | Maximum negative $F_N$ | | Maximum positive $F_N$ | |
|---|---|---|---|---|---|---|---|
| | | F-ratio | *p* value | F-ratio | *p* value | F-ratio | *p* value |
| Rake angle | 2 | 3363.6 | <0.0001 | 549.37 | <0.0001 | 267.71 | <0.0001 |
| Wavelength | 1 | 1672.1 | <0.0001 | 9.19 | 0.0026 | 93.45 | <0.0001 |
| Depth of cut | 1 | 46.0 | <0.0001 | 0.04 | 0.8511 | 0.72 | 0.3967 |
| Rake angle*wavelength | 2 | 398.8 | <0.0001 | 8.01 | 0.0004 | 2.30 | 0.1017 |
| Rake angle*depth of cut | 2 | 136.6 | <0.0001 | 3.94 | 0.0201 | 8.39 | 0.0003 |
| Wavelength*depth of cut | 1 | 10.6 | 0.0012 | 0.17 | 0.6800 | 1.56 | 0.2121 |
| Rake angle*wavelength*depth of cut | 2 | 44.2 | <0.0001 | 2.16 | 0.1168 | 10.01 | 0.0001 |
| Error | 468 | | | | | | |
| Total | 479 | | | | | | |

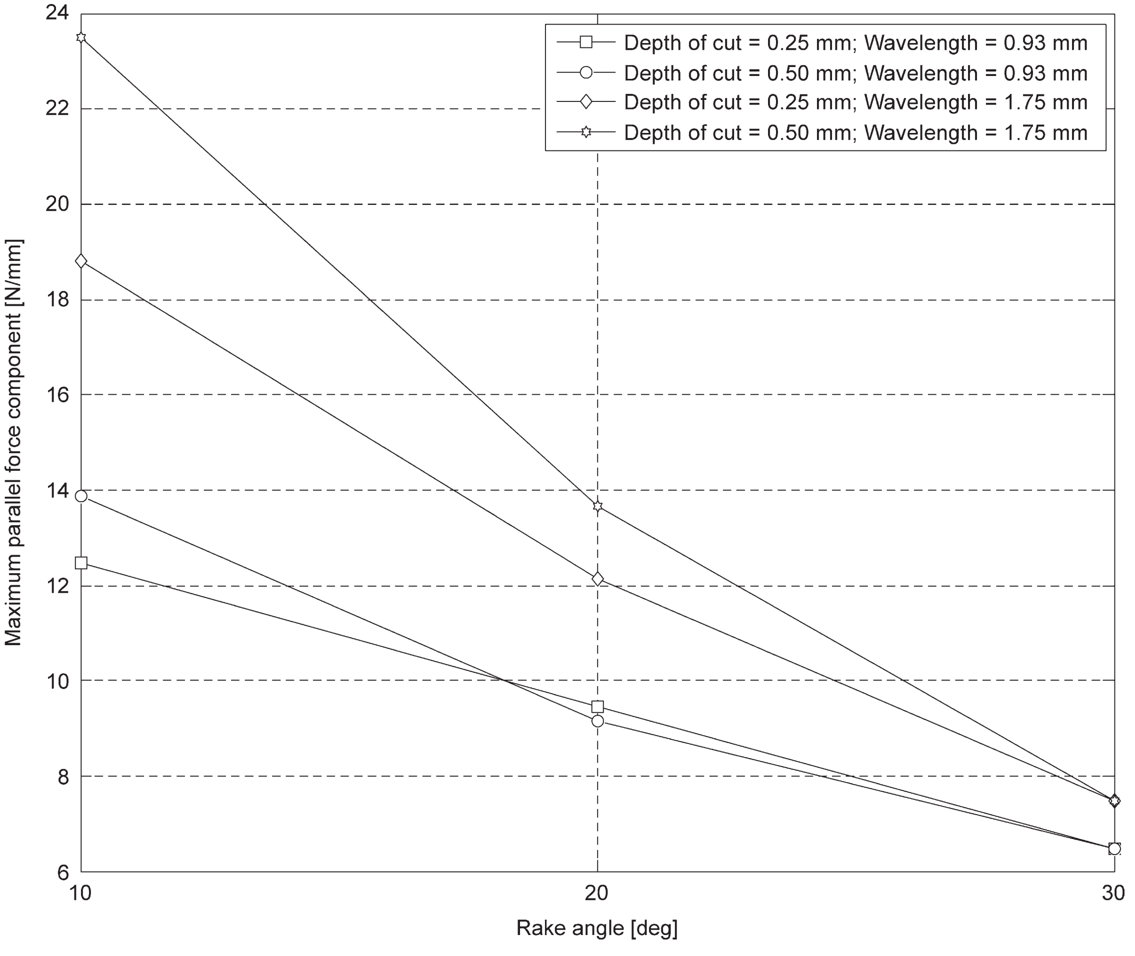


Figure 3. Maximum parallel force component as a function of rake angle, depth of cut, and wavelength.

decreasing either wavelength or cutting depth. These observations confirm what is normally carried out during machining to obtain edges free of defects.

A set of figures illustrating one cutting cycle at different rake angles when all other cutting parameters are kept constant is shown in Fig 4. At the beginning of chip formation, the cutting edge enters into the wood at a minute chip thickness and at a low angle formed between the instantaneous velocity vector and the wood grain. Cutting is hence occurring at an angle that is considered as "following the grain" (assuming that grain is exactly straight and parallel to the wood surface). The minute thickness at this point produces a chip that is easy to deform. The knife then reaches the lowest point of the wavelength, at which the angle between the instantaneous velocity vector and wood grain equals zero. At this knife position, the peripheral cutting is equivalent to 90-0. From this point, cutting progresses against the grain until the cutting edge leaves the workpiece. As the cutting cycle develops, the chip becomes thicker causing higher resistance to its formation. When rake angle of the cutting tool is low, its rake face could also take part in pushing the chip forward, causing its further deformation. As rake angle of the tool increases, its rake face will push and

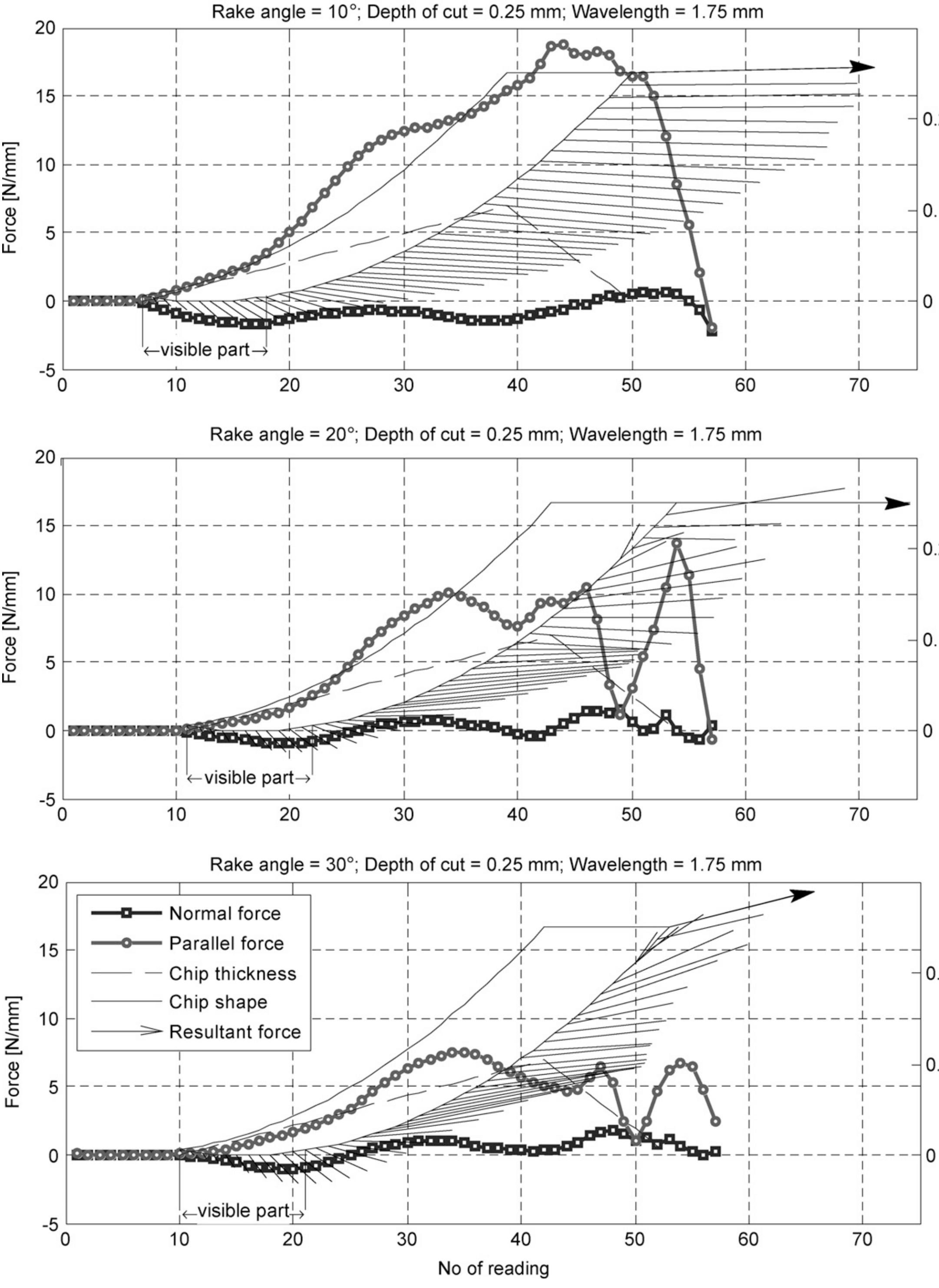


Figure 4. Effect of rake angle on cutting forces.

deform the chip to a lesser extent. Instead, the chip slides over the rake face. As thickness of the chip increases, the chip becomes more and more stiff, and consequently the stress generated perpendicular to the grain may exceed the transverse tensile strength of the wood. As a result, splitting ahead of the tool edge may occur. As rake angle increases, it becomes more likely that splitting may occur causing stress releases and, as a result, release of the force components. This explains the sudden releases of parallel and normal force components shown in Fig 4 when rake angles were 20° and more. However, splitting and releases of the parallel force component were well pronounced only when wavelength was 1.75 mm. No splitting was observed when wavelength was 0.93 mm, although rake angles were 20 or 30°. Also, the release was observed at the end of the cutting cycle. This supports the theory of splitting ahead of the cutting edge when the chip is thick enough to generate resistance that exceeds tensile strength perpendicular to the grain. Figure 4 also clearly shows the progression from type II to type I chips as rake angle increased from 10-30°. This progression is visible in the second portion of the cutting path in which sudden releases of parallel and normal forces occurred (type I chips).

## Normal Negative Force Component

Normal negative force is considered critical for defects left on the newly created surface. This force component is responsible for the amount of transverse compression that occurs when the cutting edge attacks the workpiece. Excessive compression may produce cell crushing at the surface and subsurface as indicated previously (River and Miniutti 1975; Stewart 1980; Stewart and Crist 1982). Compression might also cause raised grain, which could necessitate fine sanding operations (Palmqvist and Johansson 1999; Palmqvist 2003). The normal negative force component is therefore important given that it primarily occurs in the first stage of the cutting cycle. That is when the visible part of the wood surface is produced (Fig 2).

ANOVA showed that maximum negative $F_N$ was significantly affected by rake angle, wavelength, and the interaction between these two variables (Table 2). Effect of rake angle was by far more pronounced than that related to wavelength. Effect of rake angle on maximum negative $F_N$ depended slightly on the wavelength considered. As expected, the highest (absolute) negative $F_N$ was obtained at 10° rake angle (Fig 5, see negative values). As rake angle decreased, the cutting edge tended to push more perpendicular to the grain, which resulted in higher $F_N$. Furthermore, the contributions of friction between the rake face of tool and wood chip as well as the pushing effect of the rake face on the chip increased. These effects should have decreased as rake angle increased. However, Fig 5 shows that the lowest (absolute) maximum negative $F_N$ was recorded when rake angle was 20° and not 30°. This could be explained by differences in sharpening quality of knives used in the experiment. In fact, the sole cutterhead used had a knife slot ground at 20°. The knife used for 20° rake angle was thus only sharpened on its clearance face. Conversely, knives used for 10 and 30° rake angles had to be sharpened on their rake and clearance faces. This resulted in different rake tool face qualities between the two types of knives. Mean roughness ($S_a$) of the rake faces was 6.2 μm for knives working at 10 and 30° rake angles and 5.3 μm for the knife working at 20° rake angle. The smoother rake face of the latter knife probably contributed to decreasing maximum negative $F_N$ by decreasing friction between the rake face tool and the wood chip. It is therefore hypothesized that, within the range of values studied, the relationship between rake angle and maximum negative $F_N$ should be linear.

Effect of wavelength on maximum negative $F_N$ was slight and variable depending on the rake angle considered (Fig 5). Wavelength could rather be used to assure that the maximum negative $F_N$ is reached far away from the visible part of the cutting path. Thus, for 6 of the 12 cutting conditions studied, negative $F_N$ attained its maximum value within the visible part of the cut

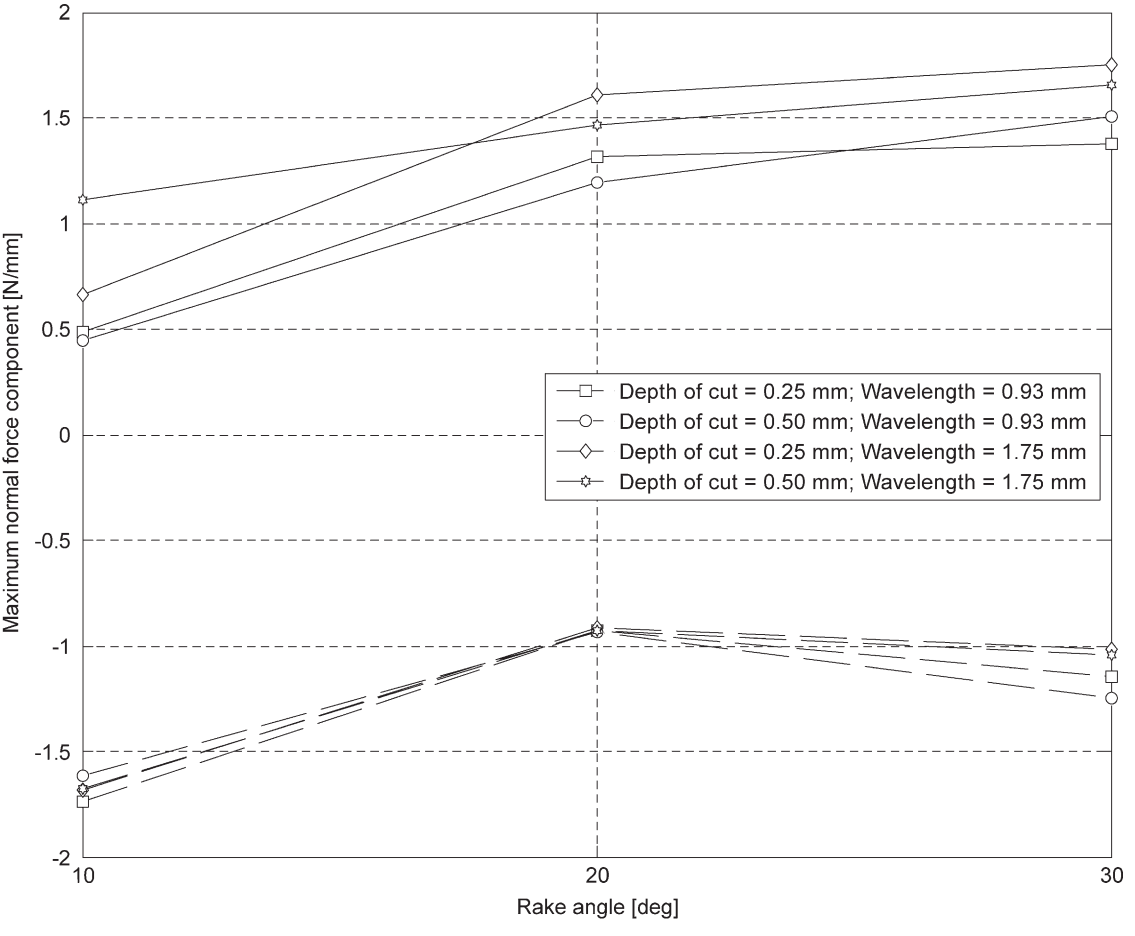


Figure 5. Maximum normal forces for both negative (pushing) and positive (pulling) components as a function of rake angle, depth of cut, and wavelength.

(Table 3). This corresponded to the six conditions tested at 1.75-mm wavelength. When wavelength decreased to 0.93 mm, maximum negative $F_N$ was observed out of this area (or at the limit).

As expected, depth of cut did not show any effect on maximum negative $F_N$ given that this parameter was not implicated at the first stage of the cutting cycle. The analysis shows that it is therefore of interest to use high rake angles to diminish the crushing action on the visible part of the cutting path. Small wavelengths can also decrease this action by transferring maximum negative $F_N$ far away from the visible part of the cut. Changes in depth of cut did not have an important impact on this phenomenon.

## Normal Positive Force Component

Normal positive cutting force is probably the principal contributor to torn grain production given that this component acts upward, ie pulling the chip from the workpiece. As the cutting cycle progressed, the knife edge left the visible region and traveled along the cutting path against the grain (Fig 2). After a certain period, normal force turned from negative to positive. From this, the positive $F_N$ component acted perpendicularly to the grain in which tensile strength of the wood is not particularly high. As soon as this force exceeded tensile strength perpendicular to grain, the chip was split following the grain. As reported by Stewart

Table 3. Proportions of the cutting path when the normal force component is in the visible portion of the path, reaches its maximum negative value, and changes from negative to positive.[a]

| Rake angle (deg) | Wavelength (mm) | Depth of cut (mm) | Length of a cutting path (mm) | Number of points (time) when $F_N$: Is in the visible part of cutting | Reaches its maximum negative value | Changes from negative to positive | Total number of points | Proportion (%) of the path when $F_N$[b]: Is in the visible part of cutting | Reaches its maximum negative value | Changes from negative to positive |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0.93 | 0.25 | 5.93 | 3 | 9 | 18 | 22 | 14 | 41 | 82 |
| | 0.93 | 0.5 | 8.39 | 4 | 9 | 19 | 30 | 13 | 30 | 63 |
| | 1.75 | 0.25 | 5.94 | 11 | 10 | 40 | 43 | 26 | 23 | 93 |
| | 1.75 | 0.5 | 8.4 | 12 | 10 | 49 | 59 | 20 | 17 | 83 |
| 20 | 0.93 | 0.25 | 5.93 | 3 | 3 | 11 | 22 | 14 | 14 | 50 |
| | 0.93 | 0.5 | 8.39 | 4 | 4 | 12 | 30 | 13 | 13 | 40 |
| | 1.75 | 0.25 | 5.94 | 11 | 8 | 15 | 43 | 26 | 19 | 35 |
| | 1.75 | 0.5 | 8.4 | 12 | 8 | 15 | 59 | 20 | 14 | 25 |
| 30 | 0.93 | 0.25 | 5.93 | 3 | 4 | 12 | 22 | 14 | 18 | 55 |
| | 0.93 | 0.5 | 8.39 | 4 | 8 | 12 | 30 | 13 | 27 | 40 |
| | 1.75 | 0.25 | 5.94 | 11 | 9 | 16 | 43 | 26 | 21 | 37 |
| | 1.75 | 0.5 | 8.4 | 12 | 10 | 17 | 59 | 20 | 17 | 29 |

[a] Results obtained during a peripheral up-milling knife cut of sugar maple wood.
[b] Proportion for each event was calculated from the number of points acquired during a cutting cycle. Precision is hence given by the distance between two points, ie it depended on the frequency of data acquisition (in this case, 16,000 samples per second).

(1969), cutting against the grain also causes deflection of fibers. Based on this, deflected and loosened fibers are more likely to be torn out before they are cut. Because of the torn grain phenomenon, the wood surface can be damaged severely and can require reworking or scrapping (Palmqvist 2003). Therefore, to limit torn grain incidence, it is essential to decrease the pulling normal force.

Factors that significantly affected the maximum positive $F_N$ component were rake angle, wavelength, and the triple interaction among rake angle, wavelength, and depth of cut (Table 2). The most significant factor affecting $F_N$ was rake angle. However, at this position of the cutting path, the effect of wavelength became more important than that observed when $F_N$ reached its maximum negative value. Thus, Fig 5 shows that maximum positive $F_N$ increased as rake angle and wavelength increased. Variation in depth of cut did not show a significant effect on maximum positive $F_N$. This factor showed erratic behavior, which was probably caused by the quite low range of values studied (0.25-0.50 mm). Splitting should be in fact more governed by the chip thickness variation. Within the range of values studied, chip thickness was more affected by wavelength than by cutting depth variations. Average chip thickness increased 41% when depth of cut varied 0.25-0.50 mm and 89% when wavelength increased from 0.93-1.75 mm (Table 1). Depth of cut could rather be used to assure that the change in $F_N$ from negative to positive is reached far away from the visible part of the cutting path. Thus, the probability of production of torn grain should be decreased by limiting the pulling action of the tool. Table 3 shows that changes in $F_N$ from negative to positive happen later for the 0.25-mm depth of cut than for the 0.50-mm depth of cut. Similarly, these changes are also later at lower rake angles than at higher rake angles.

Analysis shows that it is therefore of interest to use low rake angles and short wavelengths to diminish the pulling action of the cutting tool. Small depths of cut can also decrease this action by transferring the change in $F_N$ from negative to positive far away from the visible part of the cut.

## CONCLUSIONS

Measurements of cutting forces when up-milling sugar maple wood showed that at the initial step of the cut, $F_N$ was negative, ie the knife edge pushed the workpiece downward. The part of the knife path that remains visible on the machined surface was always created under such conditions. As the knife edge advanced in the cutting path, $F_N$ increased, reached a maximum negative value, then decreased to 0 N/mm, turned positive, and continued upward. $F_P$ was always positive and increased as chip thickness increased. Positive $F_N$ and $F_P$ reached a maximum just prior to emergence of the knife from the workpiece, ie at the maximum thickness position. However, when type I chips were produced as a result of chip splitting, maximum $F_P$ and positive $F_N$ were recorded before the theoretical maximum thickness position was reached. Maximum negative $F_N$ and $F_P$ increased as rake angle decreased and as wavelength increased. Maximum positive $F_N$ increased as rake angle and wavelength increased. Impact of depth of cut on maximum $F_P$ and maximum positive $F_N$ values was less important.

From a practical point of view, occurrence of torn edges should be avoided by using high rake angles and short wavelengths. These cutting conditions also should diminish the crushing action on the visible part of the cutting path. Short wavelengths will transfer the maximum negative $F_N$ far away from the visible part of the cut. Changes in depth of cut will not have any impact on such defects. Conversely, use of low rake angles and short wavelengths should decrease the pulling action of the knives when $F_N$ turns positive. Small depths of cut can also decrease this action by transferring the change in $F_N$ from negative to positive far away from the visible part of the cut.

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