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Effects of helical angle of router bit on acoustic emission

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Abstract The purpose of this study was to investigate the effects of changes in the helical angle of the router bit on the acoustic emission (AE) signal for various workpiece grain angles. The helical angle varied from 0° to 50° at 10° increments. The workpiece grains were oriented from 0 degrees (cutting parallel to the grain), through 90° (cutting end of the grain), to 165° at 15° increments. The AE signals and machined surface roughness were measured in an attempt to clarify the relations between them. The results were summarized as follows: (1) The AE signals were lowest in the "with the grain" cutting zones and slightly increased in the "against the grain" cutting zones; they rapidly reached the highest values at the 135°–165° grain angles. The greater the helical angle of the router bit, the smaller were the AE count rates for each grain angle investigated. There was no significant change in AE generation for helical angles of 0° and 10°. Moreover, the greater the feed rate, the greater was the AE count rate for every cutting condition investigated. (2) The surface roughness, similar to the AE count rate, had the lowest values in the "with the grain" cutting zones, slightly increased until the 120° grain angle, and then rapidly become extremely rough, reaching a maximum at the grain angles of 135°–150°. There was no remarkable change in the machined surface roughness while routing "with the grain" using the router bit of greater helical angle. However, when routing "against the grain," the greater the helical angle the smoother was the machined surface. (3) There were correlations between the AE count rate and the machined surface roughness for each helical angle investigated. Therefore, acoustic emission has shown promise for monitoring and controlling the routing operation, including various grain angles and helical angles of the router bit.

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Introduction

In recent years interest has been generated in automated systems for wood-cutting machines.[1–4] Acoustic emission (AE) has shown promise for the in-process monitoring of the cutting parameters including various cutting conditions.[1–3,5–14] Control systems using AE signals have been proposed to produce a desired surface finish by automatic control of the workpiece feed rate during circular sawing and routing.[2,3] In addition, numerous studies have been conducted to establish the relation between AE and the chip formation process.[6–11,13] It was observed that AE signals generated during wood cutting were closely related to the chip formation process. Although much information has been accumulated regarding AE in wood cutting, most basic investigations have been related to orthogonal cutting. It is essential, however, to pay more attention to a common wood-machining situation, peripheral cutting.

The purpose of this study was to investigate the effects of changes in the helical angle of the router bit on acoustic emission (AE) signals for various workpiece grain angles (inclination angles) to obtain basic knowledge on the possibility of using them to monitor and control the routing process. The AE signals and machined surface roughness were measured in an attempt to clarify the relations between them.

Experimental procedure

Cutting conditions

The experimental setup consisted of a vertical NC router as the power arbor and workpiece feed system (Fig. 1). The experiments were carried out with a router bit of sintered cemented carbide 12mm in diameter and with clearance and sharpness angles of 15° and 20°, respectively, measured at the cross section perpendicular to the longitudinal axis of the bit (Table 1). The helical angle of the router bits, defined as an angle between the bit longitudinal axis and the cutting edge tangent at the point where a plane that includes the longitudinal axis crosses the cutting edge, varied from 0° to 50° at 10° increments, as shown in Fig. 2.

Up-milling along straight lines was done during this experiment for an arbor speed of 5000rpm and routing depth and width of 10mm and 2mm, respectively (Fig. 3). Grain angles (inclination angles) were oriented from 0° (cutting parallel to the grain) through 90° (cutting end-grain) to 165° at increments of 15°. Grain angles less than 90° were "with the grain" and the ones greater than 90° were "against the grain." Yellow poplar (*Liriodendron tulipifera* Linn.) blocks were used as the workpieces. All specimens, air-dried, were conditioned to approximately 11% moisture content and 0.53 specific gravity. Cuts were made for each cutting condition (excluding sections of such wood defects such as knots or decay) to measure the AE signals, cutting force, and surface roughness.

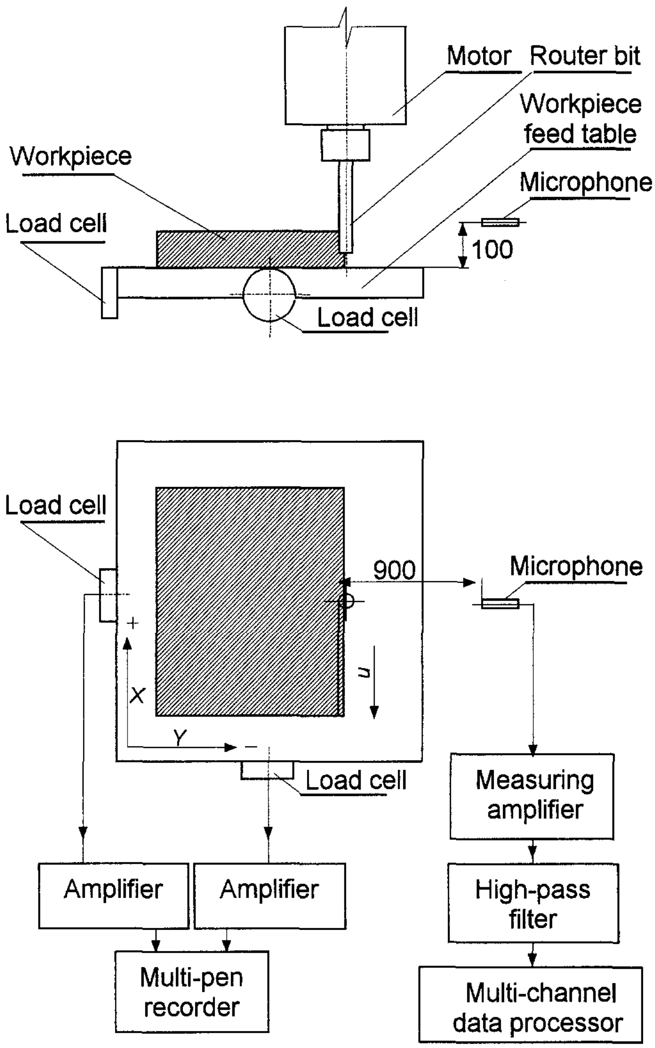


Fig. 1. Experimental apparatus. *u*, feed direction

Table 1. Cutting conditions

Factor	Conditions
Arbor speed (rpm)	5000
Workpiece feed rate (m/min)	2.0, 4.0
Grain angle (°)	0, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 160
Helical angle of the router bit (°)	0, 10, 20, 30, 40, 50
Diameter of bit (mm)	12
Bit knife number	3
Rake and clearance angle (°)	15 and 20, respectively
Workpiece	Yellow poplar (*Liriodendron tulipifera* Linn.)
Depth and width of routing (mm)	10 and 2, respectively

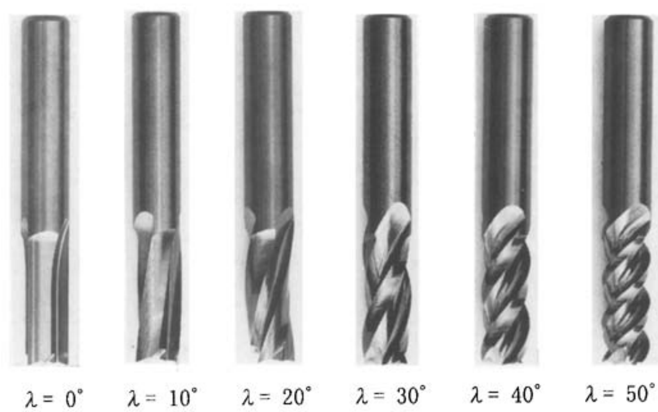


Fig. 2. Helical router bits. λ, helical angle

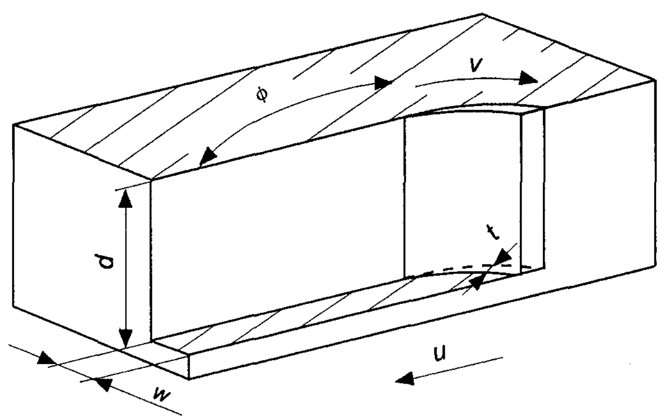


Fig. 3. Up-milling configuration. ϕ, inclination angle; d, routing depth; w, routing width; u, workpiece feed direction; v, velocity vector; t, instantaneous chip thickness

AE measurements

A microphone of −49.3 dB sensitivity and a response frequency ranging from 4 to 100 kHz was used to sense the AE signals. A condenser microphone (mentioned above), a measuring amplifier, a high-pass filter, and a multichannel data processor were used for this measurement (Fig. 1). The microphone was positioned 100 mm above the workpiece feed table, 900 mm from the router spindle, at 90° to the workpiece feed direction, as shown in Fig. 1. The AE count rate (in this study the AE count rate was expressed in counts/0.2 s) was measured by the ring-down method to characterize the AE signals when cutting. The level of the measuring amplifier, the cutoff frequency of the high-pass filter, and the preset threshold voltage of the multichannel data processor for the experiments were determined to be 50 dB, 30 kHz, and −23.6 dB, respectively.

Cutting force measurements

The horizontal *X* and *Y* component cutting forces were measured by load cells installed in the workpiece feed table, with an amplifier and a multiple pen recorder, as shown in Fig. 1. The resultant cutting force was calculated by adding vectors of the two force components, *X* and *Y*.

Surface roughness measurements

The surface roughness was measured using a stylus-type surface measuring instrument with a diamond tracer point with a tip radius of 0.25 mm. The tracer was moved perpendicular to the knife marks on the surface length of 25 mm. The measured value was expressed by the 10-point height of irregularities (*Rz*), which corresponds to the Japanese Industrial Standards (JIS B 0601 1994).

Results and discussion

Relations between AE count rates and grain angles for helical angles investigated

Figure 4 shows AE count rates as functions of grain angles for helical angles investigated at a feed rate of 4 m/min. The AE count rate, lowest in "with the grain" cutting regions, increased slightly to 90°–105° grain angles, and then rapidly reached its maximum at 135°–165° grain angles. This fact was attributed to changes in the chip formation process closely related with AE activity.[14] Moreover, the greater the helical angle of the router bit, the smaller the AE. This result was considered to be due to the change in cutting mechanism and chip formation process.[15] It relates to changes in the instantaneous amount of cut wood and the distribution of cutting forces in single chip cutting. Namely when machining with a router bit of 0° helical angle, the instantaneous amount of cut wood, lowest at the point of knife engagement into the machined material, increases proportionally to the changes in the instantaneous chip thickness as the knife moves forward, reaching its maximum near the region where the knife emerges from the

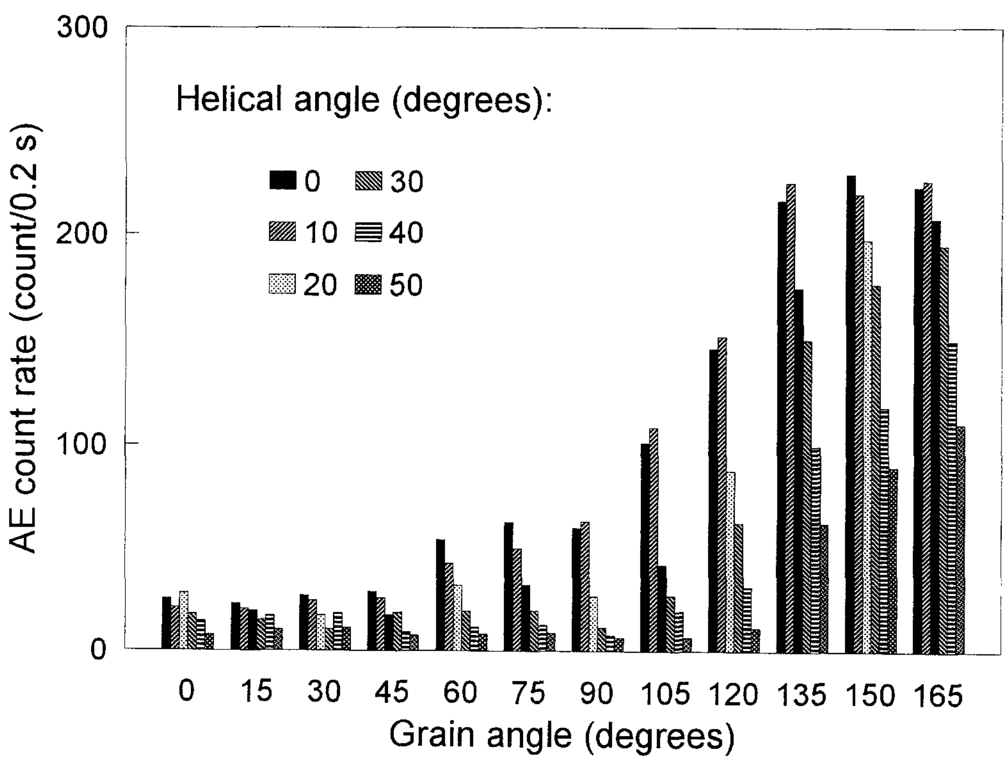


Fig. 4. Acoustic emission (*AE*) count rates as functions of grain angles for helical angles of 0°–50° at a feed rate of 4 m/min. Arbor speed, 5000 rpm; routing depth, 10 mm; routing width, 2 mm; species, yellow poplar (*Liriodendron tulipifera* Linn.)

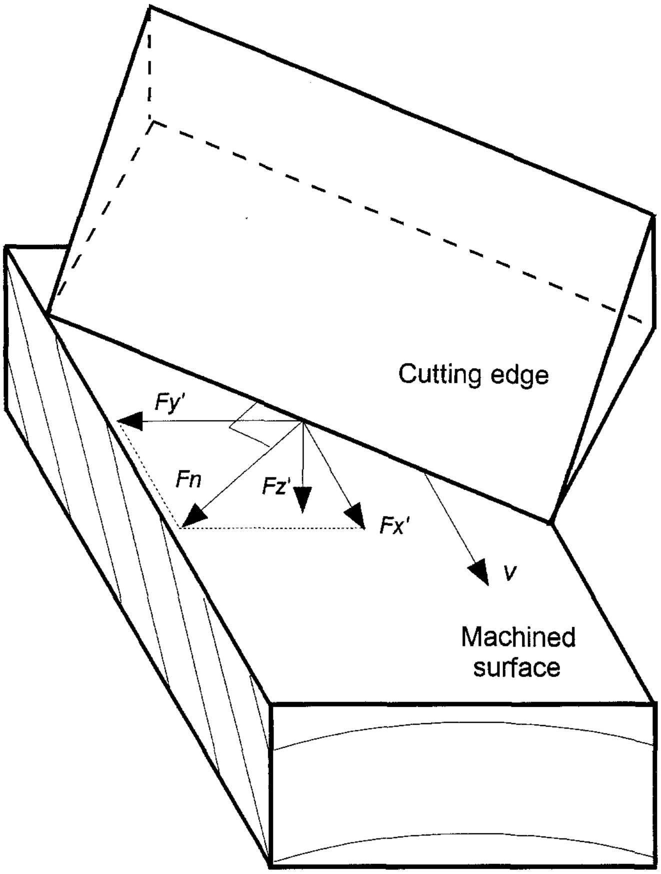


Fig. 5. Cutting forces distribution at the cutting edge during machining with a helical router bit. *V*, vector of the cutting speed related to the bit rotation; *Fn*, cutting force component perpendicular to the cutting edge in the cutting plane; *Fx'*, cutting force component in the direction parallel to the direction of the velocity vector of the bit rotation (*V*); *Fy'*, cutting force component in the direction perpendicular to the direction of the velocity vector of the bit rotation in the cutting plane; *Fz'*, cutting force component in the direction perpendicular to the cutting plane

workpiece.[16] There is an idling phase between the time at which one knife emerges from the workpiece and the next knife engages the machined material. When machining with a router bit using a helical angle greater than 0°, the cutting edge is no longer parallel to the router bit axes, and the cutting edge engages the machined material gradually. As the knife moves forward, other parts of the cutting edge come into contact with the workpiece, in addition to the parts being already engaged, and cut the chip at greater thickness. When the part of the cutting edge most ahead reaches the periphery of the workpiece and is about to cut the chip at its greatest thickness, the rest of the knife is still cutting the chip at less thickness during routing by the router bit with a helical angle less than 27°. When cutting at a width and depth of 2 and 10mm, respectively, with a router bit with a helical angle more than approximately 27°, some part of the knife is not yet engaged in cutting.[16] The knife engagement time increases, whereas the idling phase becomes shorter. Moreover, the instantaneous maximum amount of cut chip decreases, and therefore the AE generation decreases. As the helical angle continues to enlarge (approximately from 37° for the cutting conditions investigated), the second knife engages the workpiece although the previous one has not yet disengaged from it, and the idling phase thus disappears completely. As a consequence, the instantaneous amount of the cut chip increases. Some increase in AE generation would be expected owing to increases in the instantaneous amount of the cut chip.

In addition, an increase in helical angle causes changes in the distribution of the cutting forces during single chip cutting owing to the cutting edge and the rake face orientations, as shown in Fig. 5. Because the cutting force component perpendicular to the cutting edge (*Fn*) changed its direction in relation to the grain orientation for a helical angle greater than 0°, the stress distribution in the machined material at the cutting edge, as well as below and ahead of the edge, changed its orientation in relation to the grain. Considerable changes in chip formation were noted, especially in "against the grain" machining zones; and the generation of splits and cracks decreased remarkably. This phenomenon led to a significant decrease in AE activity along with a more steady cutting process, occurring at 105°–165° grain angles.

Relations between the surface roughness and grain angles for helical angles investigated

Figure 6 shows the changes in the surface roughness due to changing the grain orientation for various helical angles at a feed rate of 4m/min. The surface roughness, lowest at a grain angle of 0° slightly increased until 120°, and then rapidly became rough, reaching its maximum at grain angles of 135°–165°. There was a clear distinction of "with the grain" and "against the grain" cutting regions. At the "with the grain" cutting regions an excellent surface quality was produced, whereas cutting "against the grain" resulted in a number of machining failures, such as fuzzy grain (135° and 150° grain angles) or chipped grain (165° grain angle). Moreover, changes in the helical angle had an effect on surface roughness. Although the surface roughness values were somehow scattered, the greater the helical angle, the better was the machined surface quality in the "against the grain" routing zones (Fig. 7). This was attributed to the changes in tool geometry, mentioned above, which caused changes in stress orientation in the machined material. Almost satisfactory surface roughness was obtained for the helical angle of 50° despite a relatively fast feed rate of 4m/min. Concerning the "with the grain" zones, there was no noticeable improvement in machined surface roughness, although the surface was of excellent quality. It is also concluded that the generation behavior of acoustic emission is similar to that of surface roughness.

Relations between the cutting forces and grain angles for the helical angles investigated

Figure 8 shows resultant cutting forces as functions of grain angles for helical angles of 0°, 10°, 20°, 30°, 40°, and 50° at a

Fig. 6. Surface roughness as a function of the grain angle for helical angles of 0°–50° at a feed rate of 4 m/min

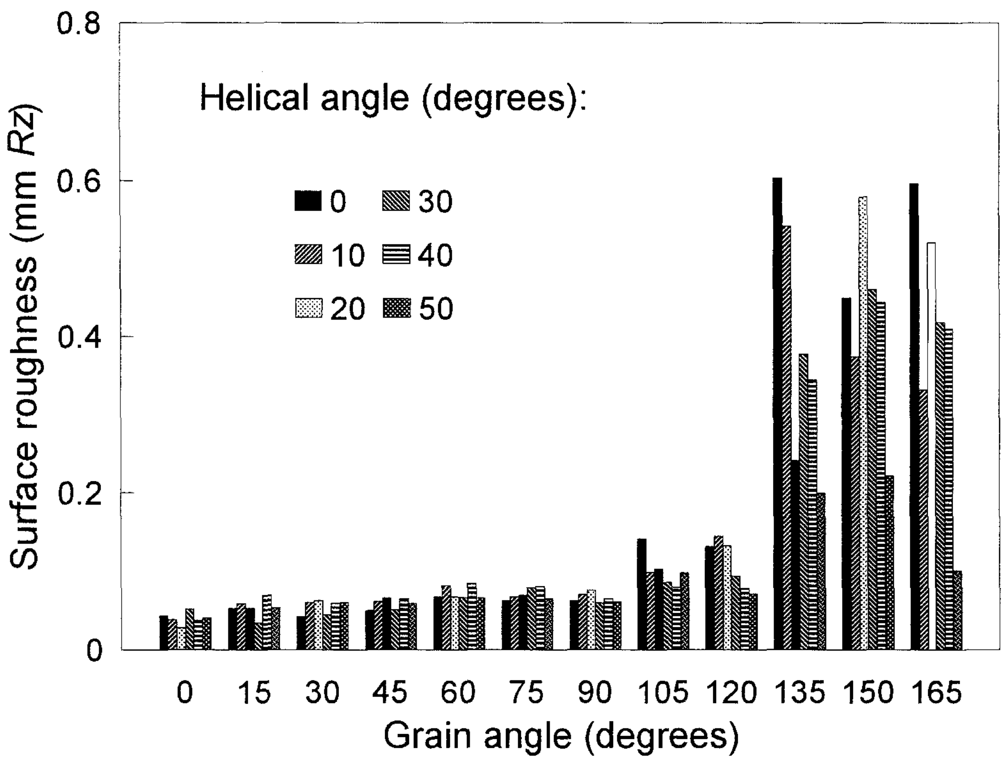
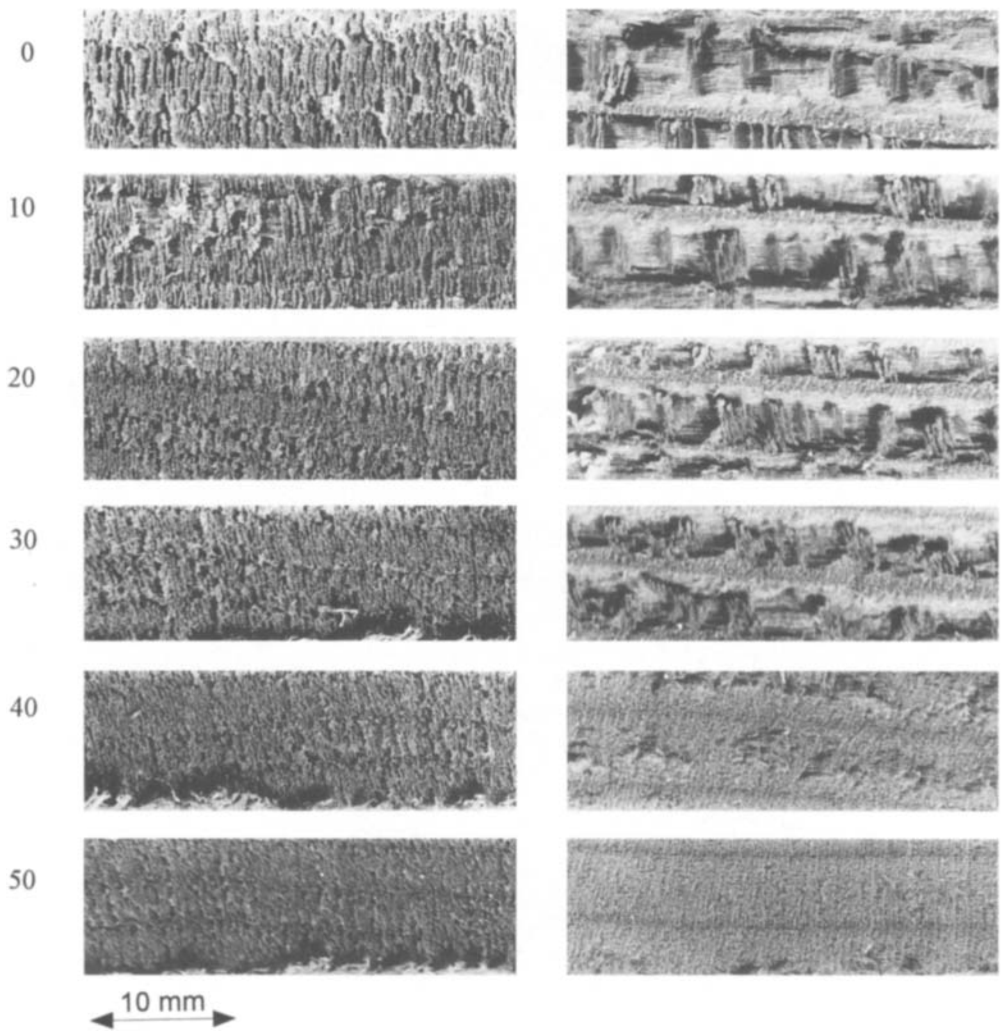


Fig. 7. Typical machined surfaces machined with router bits of various helical angles (0°–50°) at grain angles of 135° (**left**) and 165° (**right**) and a feed rate of 4 m/min



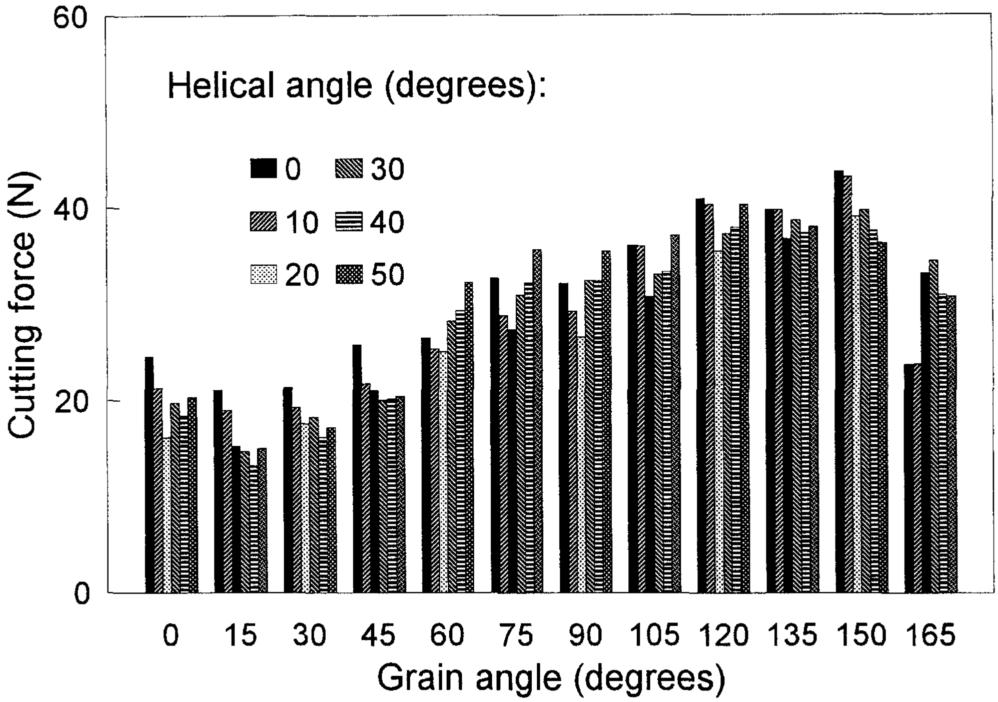


Fig. 8. Resultant cutting forces as functions of grain angles for helical angles of 0°–50° at a feed rate of 4 m/min

feed rate of 4 m/min. The cutting force slightly decrease from 0° grain angle to about 15°–30° grain angle taking the lowest values and then increased to reach a maximum at the grain angle of 120°–150°. The cutting force showed a lower value at a grain angle of 165° than at 150°. The helical angle also affected the cutting forces but not consistently. The cutting forces, although somehow scattered, showed a parabolic tendency, with a minimum at a helical angle of about 20° at most of the grain angles investigated. At grain angles of 15°, 30°, and 45° the minimum appeared somewhere around helical angles of 30°–40°. Exceptions were the grain angles of 150° and 165°, where decreasing and increasing tendencies appeared, respectively.

Relation between AE count rate and surface roughness

Figure 9 shows the relation between the AE count rate and surface roughness for all grain angles investigated, for helical angles 0°, 30°, and 50° at a feed rate of 2 m/min. The greater the AE count rate, the rougher is the machined surface. Therefore, these data were used to calculate the relations between them. Tables 2 and 3 show the results of linear regression analysis for each helical angle investigated at 2 and 4 m/min feed rates, respectively. The tables show that most correlation coefficients have values greater than 0.9 for the correlations investigated. The surface roughness may be monitored on-line by measuring the AE signals.

Table 4 shows the results of linear regression analysis of surface roughness as a function of cutting force for each helical angle investigated at a feed rate of 4 m/min. Note that most correlation coefficients have values much lower than those for the AE count rate. It is concluded that cut-

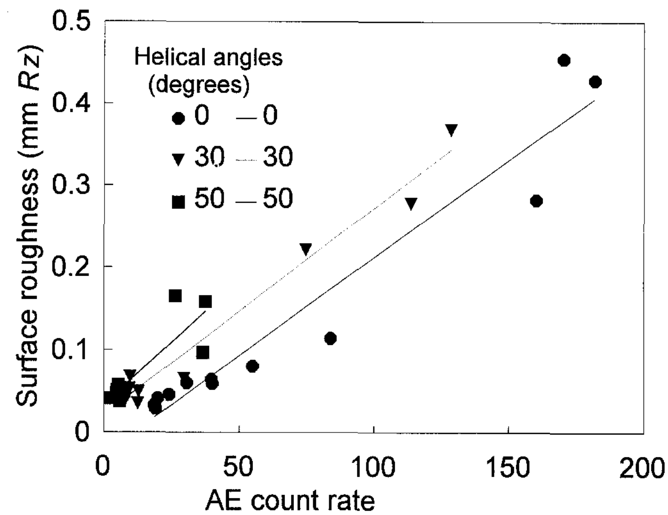


Fig. 9. Surface roughness as a function of AE count rates (counts/0.2 s) for helical angles of 0° (*circles*), 30°, (*triangles*), and 50° (*squares*) at a feed rate of 2 m/min

Table 2. Relations between surface roughness and AE count rate for router bit helical angles of 0°–50° at a feed rate of 2.0 m/min

Helical angle (°)	*Rz* as a function of AE count rate	Correlation coefficient
0	$y = 0.0024x - 0.0264$	0.97
10	$y = 0.0015x + 0.0124$	0.96
20	$y = 0.0019x + 0.0332$	0.97
30	$y = 0.0025x + 0.0208$	0.99
40	$y = 0.0017x + 0.0485$	0.78
50	$y = 0.0030x + 0.0333$	0.87

Rz, surface roughness (*y*, millimeters); AE, acoustic emission (*x*, counts/0.2 s).

Table 3. Relations between surface roughness and AE count rate for router bit helical angles of 0°–50° at a feed rate of 4.0 m/min

Helical angle (°)	*Rz* as a function of AE count rate	Correlation coefficient
0	$y = 0.0018x - 0.0345$	0.93
10	$y = 0.0012x + 0.0043$	0.91
20	$y = 0.0014x + 0.0212$	0.98
30	$y = 0.0016x + 0.0133$	0.98
40	$y = 0.0010x + 0.0457$	0.76
50	$y = 0.0010x + 0.0421$	0.81

Table 4. Relations between surface roughness and resultant cutting force for router bit helical angles of 0°–50° at a feed rate of 4.0 m/min

Helical angle (°)	*Rz* as a function of cutting force	Correlation coefficient
0	$y = 0.0109x - 0.1440$	0.39
10	$y = 0.0114x - 0.1681$	0.61
20	$y = 0.0161x - 0.2676$	0.70
30	$y = 0.0127x - 0.2165$	0.68
40	$y = 0.0087x - 0.0949$	0.51
50	$y = 0.0018x - 0.0055$	0.51

x, cutting force.

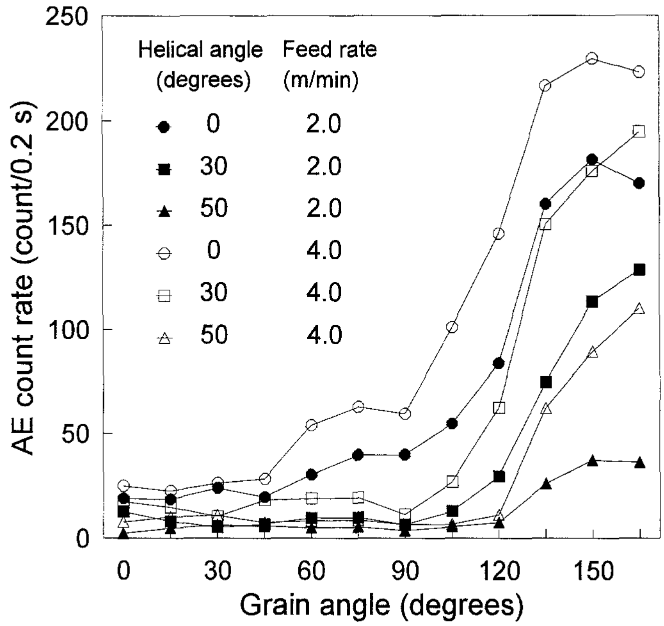


Fig. 10. Effects of feed rates on AE count rates for helical angles of 0° (*circles*), 30° (*squares*), and 50° (*triangles*). *Filled symbols* are for a feed rate of 2.0 m/min; *open symbols* are for a feed rate of 4.0 m/min

ting force monitoring of the routing process is inferior to AE monitoring for the cutting conditions investigated.

Effects of feed rates on AE generation and surface roughness

Figure 10 shows the effects of feed rates on AE generation for helical angles of 0°, 30°, and 50°. The faster the feed rate, the greater is the energy involved when removing cut material, and the more severe the machining failures. Therefore, the greater was the AE count rate for each cutting condition investigated. Figure 11 shows the effects of feed rates on surface roughness for helical angles of 0°, 30°, and 50°. The faster the feed rate, the greater are the tooth marks and the instantaneous cut chip thickness. The latter is considered to have great influence on the chip formation process and therefore on the increase in surface roughness.

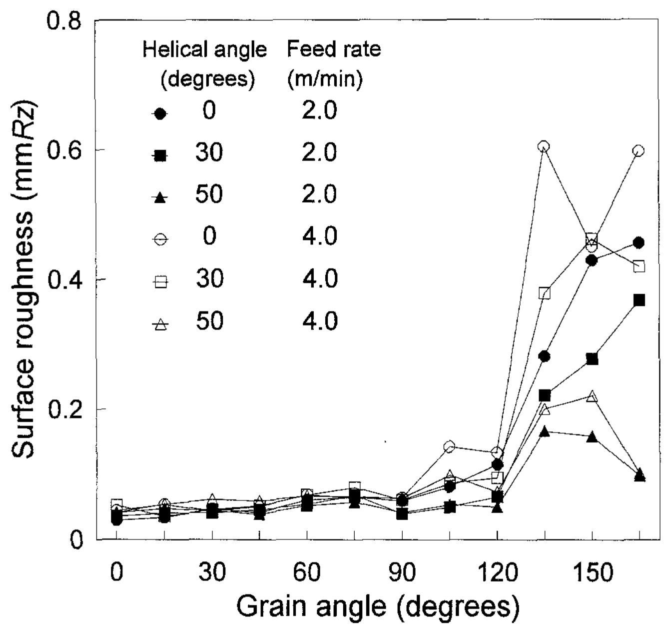


Fig. 11. Effects of feed rates on surface finish roughness for helical angles of 0°, 30°, and 50°. See Fig. 10 for explanation of symbols

Conclusion

The purpose of this study was to investigate the effects of changes in the helical angle of the router bit on the AE signal for various workpiece grain angles. The AE signals and machined surface roughness were measured in an attempt to clarify the relations between them. The results can be summarized as follows.

The AE count rate was lowest in the "with the grain" cutting zones and then increased in the "against the grain" cutting zones; it reached the highest values at 135°–165° grain angles. The greater the helical angle, the smaller were the AE count rates for each grain angle investigated, but the tendency of AE activity, in terms of grain orientation, was the same. In addition, the greater the feed rate, the greater was the AE count rate for each cutting condition, although the generation behavior of the AE with "with the grain" and "against the grain" machining conditions was similar.

The surface finish roughness, similarly to the AE count rate, had the lowest values in the "with the grain" cutting zones; it slightly increased up to a 120° grain angle and then rapidly became extremely rough, reaching its maximum at grain angles of 135°–150°. There was no remarkable change in the machined surface roughness while routing "with the grain" using the router bit with a greater helical angle. However, when routing "against the grain," the greater the helical angle, the smoother was the machined surface.

There were correlations between the AE count rate and the machined surface roughness for each helical angle investigated. Therefore, AE has shown promise for monitoring and controlling the routing operation, including various grain angles and various helical angles of the router bit.

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