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Effect of tool angles on the chips generated during milling of wood by straight router-bits

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Abstract The effect of tool angles on the shapes of chips generated by parallel-to-grain and end-grain milling was explored for China fir and maple under fixed spindle and feed speeds and cutting depth. The milling path was up-milling by straight router-bits with a diameter of 12mm. The chip shapes could be distinguished as five types: spiral, splinter, flow, thin, and granules or powder. The flow and thin chips were generated most often (on a weight percentage basis) for all tool angles investigated for parallel-to-grain and end-grain milling of China fir and maple. More granule chips were produced with parallel-to-grain milling than with end-grain milling for both woods. The measured chip thickness (t') was thicker than the calculated thickness (t_{max}). Thicker and longer maple chips were produced by end-grain milling than by parallel-to-grain milling. The tool geometries of 40°/15° (sharpness of the angle–rake angle), 50°/15°, and 60°/15° for China fir and 40°/25°, 50°/5°, and 60°/5° for maple produced relatively more flow chips with parallel-to-grain milling. Furthermore, the tool geometries of 40°/5°, 50°/15° and 60°/25° produced more flow chips (weight percentage) by end-grain milling of China fir and maple.

Key words Chip length · Chip thickness · Milling · Tool geometry · Router-bits

Introduction

The use of computer numerically controlled (CNC) machines is becoming more important in the manufacturing sequence of many furniture and cabinet firms. An earlier article reported that CNC routers appeared to be the most popular woodworking machine, and at least one is present for every eight or nine plants.[1] It is known that milling woods by the CNC router always produces a large quantity of chips, which are collected through a dust pipe usually mounted on the cutting spindle of the CNC router. Therefore, there may be some problems during such milling. For instance, the larger chips block the pipe of dust collector or twine around the tool body, and the smaller chips adhere to the edge of the router-bit. All of these events affect cutting performance. Furthermore, very tiny chips in the air create a serious health hazard for workers.[2] Numerous studies have been done to evaluate the cutting force, acoustic emission (AE), tool wear, sound pressure level, and so forth, but the number of studies on chip formation by routers are limited. Ikegiwa and Harima[3] were concerned with the adhesion of dust particles to cutting edges. Palmqvist and Gustafsson[4] studied the relation between some critical factors for planing and the creation of dust with a diameter of less than 10μm.

Because of the small diameter of the router-bit, the chips generated during milling is quite different from that while planing or shaping chips. A previous study demonstrated that chip formation was affected by the feed speed and the depth of the cut while routing.[5] The main objective of this study was to examine the influence of tool angles of the router-bit on chips generated under fixed spindle and feed speeds and cutting depth.

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Materials and methods

Materials and tools

China fir (*Cunninghamia lanceolata*) and maple (*Acer saccharum*) comprised the workpieces. Tested specimens had dimension of 100 (L) × 65 (T) × 36 (R) mm. The specific gravities of China fir and maple were 0.38 and 0.68, respectively. Moisture contents for China fir and maple were about 9% and 7%, respectively. A plane of 100 × 36 mm was machined by the straight router-bits for parallel-to-grain milling, and a plane of 65 × 36 mm was machined for end-grain milling. The straight router-bits have a diameter of 12 mm and two cutting edges of high-carbon steel with a length of 69 mm. To reduce the experimental complexity, one of the two blades was overground about 0.5 mm intentionally to carry out one-knife cutting. The sharpness angles (β) were 40°, 50°, and 60°. The rake angle (α) varied from 5° to 25°, in 10° increments. The combination of the sharpness angle and rake angle was represented by the tool geometry $\beta°/\alpha°$ (e.g., a tool geometry of 40°/5°).

Cutting conditions

The router-bit was mounted in a CNC router. The tool paths were up-milling for both parallel-to-grain and end-grain milling. The feed speed, spindle speed, and cutting depth were all fixed. The cutting conditions were as follows: sharpness angle (β): 40°, 50°, 60°; rake angle (α): 5°, 15°, 25°; spindle speed 12 000 rpm; feed speed 2400 mm/min; cutting depth 2 mm; cutting width 12 mm; feed per knife (f) 0.2 mm.

Three specimens were tested for each case. Each specimen was milled five times.

Analysis of chip formation

To determine the types of chip generated during milling, the chips were sieved by steel screens of 3.5-mesh (diameter of holes 5.66 mm), 7-mesh (diameter of holes 2.83 mm), 16-mesh (diameter of holes 1.19 mm), and 30-mesh (diameter of holes 0.59 mm) steel screens. These sieved chips were analyzed according to the chip type; the weight percentage of each chip type; the measured chip thickness (t'), which corresponds to the maximum chip thickness (t_{max}); and the measured chip length (L'), which corresponds to the contact arc length (L) (Fig. 1). The chip was stuck on a tape on which the chip length (L') and the chip thickness (t') (equivalent to the portions of t_{max}) were measured by a digital caliper. The calculated maximum chip thickness(t_{max}) and chip length (contact arc length, L) shown in Fig. 1 could be approximated by Eqs. (1) and (2).[6] Because the 16-mesh maple chips matched the ideal chip form relatively well, their measured thicknesses and lengths were compared with the calculated values.

$$t_{max} \doteqdot \frac{2F}{N \times z}\sqrt{\frac{h}{D}\left(1-\frac{h}{D}\right)} \tag{1}$$

where F is the feed speed, N is the spindle speed (rpm), z is the number of cutting blades, h is the depth of cutting, and D is the tool diameter.

$$L \doteqdot D \times \pi \times \frac{\omega}{360°} \tag{2}$$

where L is the calculated chip length, and ω is the rotation angle.

$$\omega = \cos^{-1}\frac{R-h}{R}$$

where R is the radius of the tool.

Results and discussion

Chip shapes

Although the chips were sieved by screens of four sizes, differently shaped chips were included in each screen. Thus, the chips were further distinguished into five groups according to their shape. The five groups of chips were defined as spiral chips (Fig. 2A), splinter chips (Fig. 2B), flow chips

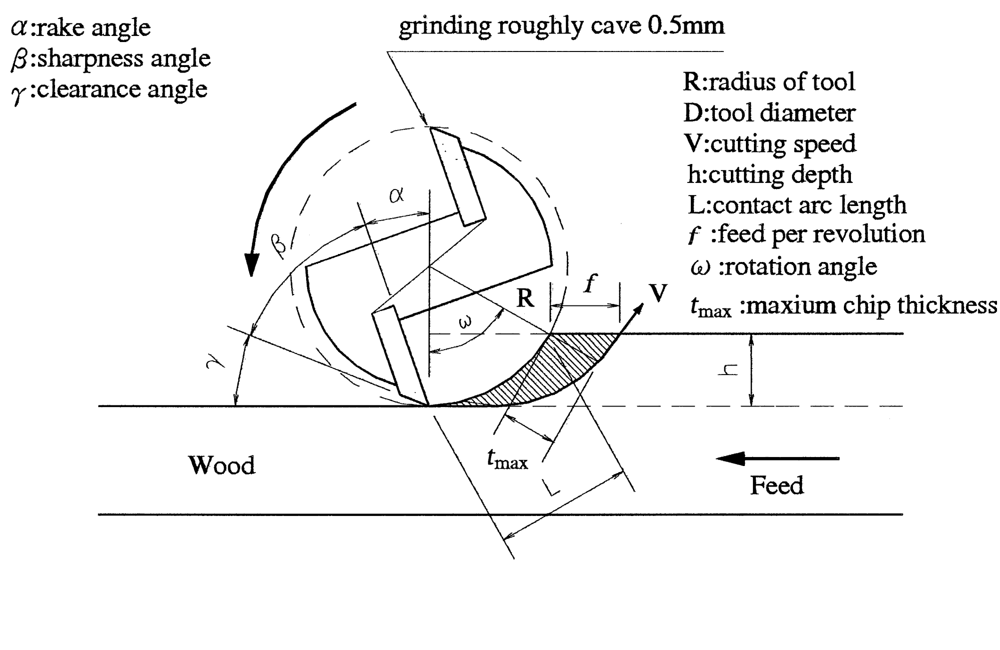

Fig. 1. Chip formation during up-milling

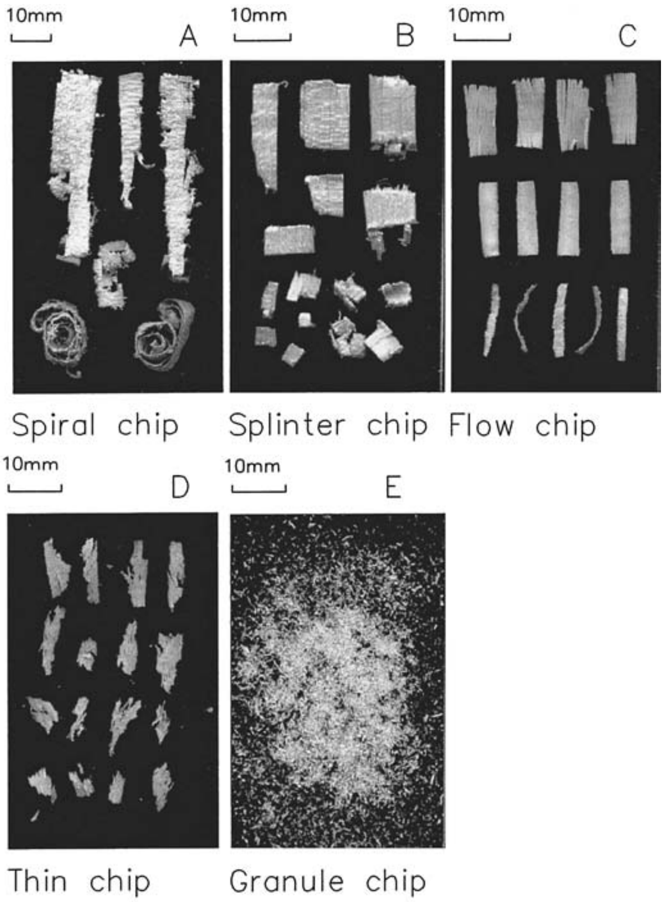

Fig. 2. Chip shapes of China fir and maple generated by up-milling with straight router-bits. **A**, chips of China-fir; **B–D**, chips of maple

(Fig. 2C), thin chips (Fig. 2D), and granule or powder chips, (Fig. 2E). Spiral chips, which were found only among the China fir chips, were wood chips that were incompletely severed owing to their relatively soft, ductile property. The splinter chip was thought to be generated by the instantaneous impact of the cutting edge on the wood, causing block chips torn along the grain.[6] The flow chip matched the shape of the theoretical milling model, as shown in Fig. 2C. The thin chip was similar to the flow chip but was somewhat smaller. Although the initial cut is substantially parallel to the grain, the emerging cut has a considerable angle to the grain during parallel-to-grain milling. On the other hand, the initial cut is perpendicular to the grain during end-grain milling. The emerging and initial milling may relate to the generation of granule chips during parallel-to-grain and end grain milling, respectively. The broken pieces of thin chips also included granule chips.

Distribution of chips

The weight percentage distribution of different chip sizes sieved by four screen sizes is shown in Table 1. The distributions are different for different cutting materials under the same cutting condition or for the same cutting material under different cutting conditions. The major shapes of chips in 3.5 mesh and 7.0 mesh were the splinter chip (Fig. 2B) with parallel-to-grain milling for both cutting species. China fir chips contained a large number of spiral chips (Fig. 2A) in addition to the splinter type in the 3.5-mesh category. The chips caught by the 16 mesh sieve are mostly flow chips (Fig. 2C). The major shapes for chips in 30 mesh sieves and smaller were thin chips (Fig. 2D) and granule chips (Fig. 2E) for both species. Table 1 shows that the tool

Table 1. Weight percentage of chips of China fir and maple

Cutting type and angle (β/α)	China fir weight percentage (%)					Maple weight percentage (%)				
	<30 Mesh (G)	30 Mesh (T)	16 Mesh (F)	7 Mesh (S)	3.5 Mesh (S, SP)	<30 Mesh (G)	30 Mesh (T)	16 Mesh (F)	7 Mesh (S)	3.5 Mesh (S)
Parallel-to-grain										
40°/5°	14.9	28.5	37.6	16.3	2.7	14.8	11.7	56.5	11.2	5.8
40°/15°	3.0	30.6	50.5	12.9	3.0	10.8	10.7	55.6	15.8	7.1
40°/25°	11.9	21.6	43.0	18.2	5.3	19.0	19.0	53.9	7.4	0.7
50°/5°	16.8	30.5	13.8	8.7	30.2	14.1	14.8	54.9	10.0	6.2
50°/15°	21.5	38.8	23.1	8.4	8.2	24.3	19.3	40.4	11.5	4.5
50°/25°	23.4	37.6	20.7	8.0	10.3	12.0	18.0	50.7	14.1	5.2
60°/5°	14.1	39.6	26.4	15.0	4.9	12.6	18.5	59.3	9.4	0.2
60°/15°	13.6	35.0	36.1	12.0	3.3	23.9	21.2	38.4	11.1	5.4
60°/25°	22.3	40.3	12.0	7.0	18.4	13.0	17.2	57.6	10.2	2.0
End-grain										
40°/5°	25.3	15.9	55.7	3.1	–	0.7	0.6	6.9	91.8	–
40°/15°	32.7	31.1	35.0	1.2	–	0.7	4.5	16.8	74.2	–
40°/25°	26.6	29.0	42.6	1.8	–	3.9	1.9	8.4	85.8	–
50°/5°	36.0	36.6	26.8	0.6	–	6.9	4.8	30.3	58.0	–
50°/15°	19.4	22.6	57.5	0.5	–	2.4	1.8	17.8	78.0	–
50°/25°	25.2	25.0	48.4	1.4	–	3.2	1.9	15.0	79.9	–
60°/5°	28.3	34.0	36.6	1.1	–	1.8	1.2	13.9	82.2	–
60°/15°	31.8	32.3	35.0	0.9	–	2.7	2.5	47.3	47.5	–
60°/25°	21.0	20.7	52.7	5.6	–	2.8	1.6	35.0	61.6	–

β, sharpness angle; α, rake angle; G, granule chip; T, thin chip; F, flow chip; S, splinter chip; SP, spiral chip
(G), (T), (F), (S), and (S, SP) indicate the major chip shape in each screen

Table 2. Measured chip thickness and chip length of 16-mesh maple chips

Angle	Parallel-to-grain		End-grain	
(β/α)	t' (mm)	L' (mm)	t' (mm)	L' (mm)
40°/5°	0.32 (0.04)	2.22 (0.15)	0.43 (0.02)	3.54 (0.10)
40°/15°	0.31 (0.04)	2.06 (0.16)	0.38 (0.02)	5.21 (0.24)
40°/25°	0.27 (0.02)	1.97 (0.17)	0.36 (0.02)	4.21 (0.34)
50°/5°	0.29 (0.02)	1.74 (0.14)	0.36 (0.02)	4.21 (0.18)
50°/15°	0.32 (0.02)	2.33 (0.13)	0.34 (0.02)	4.34 (0.20)
50°/25°	0.31 (0.02)	2.65 (0.17)	0.32 (0.02)	5.23 (0.42)
60°/5°	0.31 (0.04)	2.08 (0.12)	0.32 (0.02)	5.77 (0.20)
60°/15°	0.29 (0.02)	2.10 (0.19)	0.36 (0.02)	5.00 (0.34)
60°/25°	0.31 (0.04)	2.40 (0.19)	0.34 (0.02)	5.22 (0.16)

Values for t_{max} and L were calculated from Eqs. (1) and (2) and were 0.15 and 5.05 mm, respectively
Numbers in parentheses are standard deviations
The milling type was up-milling
t', chip thickness; L', chip length

geometries of 50°/5°and 60°/25° generated numerous splinter or spiral chips (3.5 mesh) compared with the other tool geometries. A sharpness angle of 40° in combination with the three rake angles produced more flow chips (16 mesh) than any of the other tool geometries for the parallel-to-grain milling of China fir. The other two sharpness angles (50° and 60°) showed that thin chips (30 mesh) were the major component after parallel-to-grain milling of China fir. On the other hand, flow chips were produced most often in terms of the weight percentage for all tool geometries by parallel-to-grain milling of maple, though granule chips were produced much more than with tool geometries of 50°/15° or 60°/15°. A comparatively large number of flow and thin chips were generated by the tool geometries 40°/25°, 50°/5°, and 60°/5° during parallel-to-grain milling of maple.

Most of the chips generated by end-grain milling were the flow type for almost all tool geometries except China fir chips in the 7-mesh screen, in which a small quantity of splinter chips were found. A large number of flow chips of China fir were generated in the weight percentage ranging from 26.8% to 57.5% in 16-mesh screens. The intact form of maple chips also had the largest weight percentages in 7-mesh screens for all tool geometries during end-grain milling. The chips in the 7-mesh sieve obtained by end-grain milling of maple were grouped with flow chips. For end-grain milling of China fir and maple, the tool geometries of 40°/5°, 50°/15°, and 60°/25° may be better choices to produce a relatively larger number of flow and thin chips and fewer granule chips.

Chip thickness and length

The calculated maximum chip thickness (t_{max}) and width (L) were 0.15 mm and 5.05 mm, respectively. Table 2 shows the measured chip thickness (t') and chip length (L') for 16-mesh maple chips produced by different tool geometries. As can be observed, the measured chip thicknesses (t') shown in Table 2 were larger than the calculated thickness (t_{max}). The measured chip thicknesses obtained with parallel cutting did not exhibit significant differences among the various rake angles for sharpness angles of 50° and 60°; but for a sharpness angle of 40° the chip thickness decreased with an increased rake angle. A decrease in thickness for sharpness angles of 40° and 50° was observed during end-grain milling with an increase in rake angle; a similar trend was not found for the sharpness angle 60°.

In contrast, the measured chip length was dramatically shorter than the calculated chip length for parallel-to-grain milling but was quite close to the calculated value for end-grain milling. The longest chip length was 5.77 mm, and the shortest length was only 1.74 mm under all cutting conditions. Results also indicated that the chip length decreased with increasing rake angle for the sharpness angle 40° during parallel milling, whereas this trend was reversed for sharpness angles of 50° and 60°. Although the initial cut is made substantially parallel to the grain for parallel-to-grain milling, the emerging cut is perpendicular to the grain. This could produce crushing parallel to the grain, which would result in chip separation through tension perpendicular to the grain (i.e., advance splitting).[6] On the other hand, the cutting edge that emerges from the workpiece surface is parallel to the grain for end-grain milling. The chips were generated by the successive engagement of cutting during which the chip could not be torn easily. Therefore, the chips obtained from end-grain milling are always thicker and longer than those produced by parallel-to-grain milling.

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