J Wood Sci (2002) 48:126–131

ORIGINAL ARTICLE

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Effect of the helix angle of router bits on chip formation and energy consumption during milling of solid wood

Received: July 25, 2000 / Accepted: April 13, 2001

Abstract The effect of the helix angle of a router bit on chip formation and electric energy per volume (specific energy) under different feed speeds and cutting depths during the milling of maple and China fir by a computer numerically controlled (CNC) router was investigated. The peripheral cutting edge of router bits were custom-made at helix angles of 0°, 2°, 4°, 6°, and 8°. The feed speed varied from 600 to 4800 mm/min, and the depths of cut were set at 1, 2, 3, 4, and 6 mm. The chips were classified by sieving into a flake type, a splinter type (5 and 10 mesh), a flow type (20 and 40 mesh), and a granule type (< 40 mesh). As the feed speed and the cutting depth increased for the five router bits, more chips of the flake type and the splinter type were produced. However, the number of granule-type chips under the larger helix angle was reduced. The energy per volume removed (specific energy) increased with the feed speed and the depth of cut while milling maple and China fir. More specific energy per cubic centimeter was consumed under the lower feed speeds and the smaller depth of cut. The specific energy can be expressed as a negative power function of the feed speed or the cutting depth for maple and China fir.

Key words Chip formation · Energy consumption · Milling · Helix angle · Router bit

Introduction

Wood machining is a mechanical process whereby the profile of a wood workpiece is changed. Therefore, chip formation, which results in a change in the profile of the workpiece, is fundamental when studying the machining process. Most studies of wood chip formation are based on the orthogonal or two-dimensional cutting process. For instance, Koch[1,2] took pictures of chips leaving the planer edge during lumber planing. The computer numerically controlled (CNC) cutting systems have been attached to many wood-cutting machines to improve the efficiency and accuracy of the machining processes. Accordingly, studies of cutting resistance, cutting noise, and other related characteristics of router bits of small diameter used in the CNC router have received much attention. Komatsu[3] studied the effect of the helix angle of router bits on cutting force and machined-surface roughness. Yokochi and Kimura[4] studied the relation between the helix angle of router bits and cutting resistance during a single engagement.

Chip formation was not the main issue studied in the aforementioned studies. Some situations concerning chip formation during machining should be considered. For instance, the chips might block the pipe of the dust collector or could possibly build up in the edge of a router bit, which in turn could affect the cutting performance. Therefore, chip formation is an important issue. Another issue that should be taken into consideration is the power consumption of the CNC router during the cutting process. To decrease energy consumption, it is important to select suitable cutting conditions and cutting tool. Morita et al.[5–7] measured the cutting power consumption of diamond-coated cemented carbide tools under various sharpness angles, spindle speeds, and work materials. Cutting power consumption might be considered another index of cutting performance. Based on the above considerations, the objectives of this study are to investigate chip formation and the energy consumed associated with router bits of different helix angles.

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Materials and methods

Materials

Hard maple (*Acer saccharum*) and China fir (*Cunninghamia lanceolata*) were used as the workpiece.

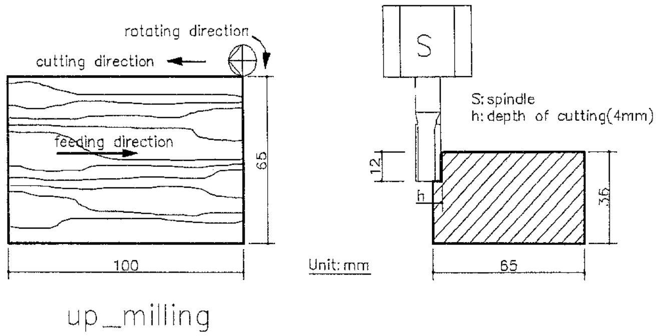


Fig. 1. Tool paths of up-milling

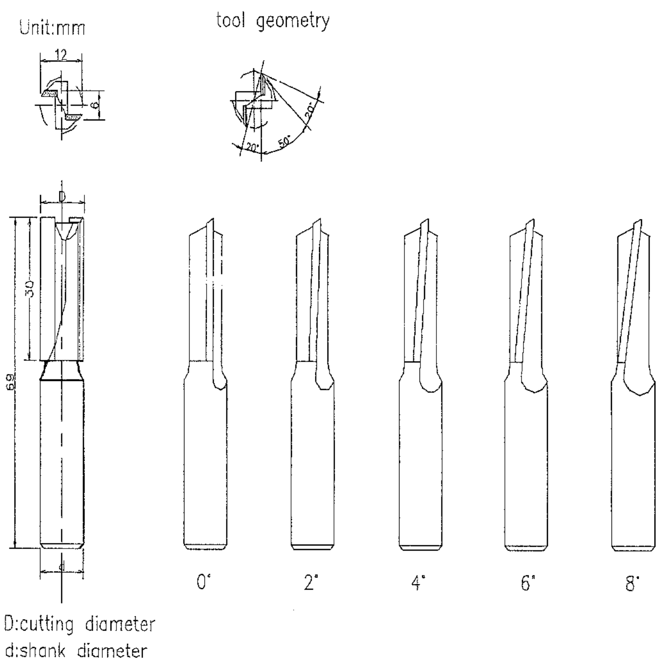


Fig. 2. Tool geometry

The test specimens had dimensions of 100 × 65 × 36 mm (longitudinal × radial × tangential), and were placed in a conditioning room at a temperature of 20°C and relative humidity of 65% before the test. The specific gravity of hard maple was 0.68, and that of China fir was 0.38. The moisture contents for hard maple and China fir were about 7% and 9%, respectively. The radial face was used as the cutting surface, with the router bits cutting along the grain direction. Figure 1 shows the specimen dimension and the cutting path. The router bits have a diameter of 12 mm and two cutting edges of high-carbon steel. The distance between the two cutting circles produced by the two cutting edges was less than 0.03 mm. The rake and clearance angles were both 20°. The sharpness angle was 50°. Five helix angles of 0°, 2°, 4°, 6°, and 8° were used. The tool geometry is shown in Fig. 2.

Peripheral milling experiment

The router bit was mounted in a CNC router. The tool path was up-milling along the grain direction, as shown in Fig. 1. The spindle speed was fixed at 12000 rpm, and the cutting width was 12 mm, equal to the diameter of the router bits. Two cutting conditions were adopted for the five helix angles. One condition was that the feed speeds were set at 600, 1200, 2400, 3600, and 4800 mm/min, respectively, when the depth of cutting was fixed at 4 mm to investigate the effect of the feed speed. Five depths of cut (1, 2, 3, 4, and 6 mm) were applied in the other condition in which the feed speed was set to be 4800 mm/min. The aforementioned conditions would result in 50 situations. Three specimens were tested for each case, and each specimen was milled five times. The collected chips were sieved by steel screens of 5, 10, 20, and 40 mesh. Fifty chips were randomly selected from each batch of sieved sample chips to measure their sizes. Chips larger than 20 mesh were measured by an electronic vernier caliper. Chips smaller than 40 mesh were subjected by a scanner to obtain an image file. The image file was then processed by AutoCAD software to measure the chip size. The scanned image size was calibrated by the actual size.

The net voltage and the net current of the main motor and the table-driven motor were measured for each case to calculate the power consumed. The power (in watts) was obtained by multiplying the voltage by the current. The energy was then computed from the power by multiplying by the cutting time. The cutting time (T_c) in seconds can be expressed by $T_c = (L \times 60)/(f \times N)$, where L is the feed length (100 mm), f is the feed per revolution, and N is the main spindle speed (12000 rpm). Therefore, the cutting time is directly dependent on the feed per revolution. The feeds per revolution were 0.025, 0.05, 0.1, 0.15, and 0.2 mm/rev for feed speeds of 600, 1200, 2400, 3600, and 4800 mm/min, respectively. To be applicable practically, the specific energy is defined as the energy per volume where the volume is expressed in cubic centimeters. In such a way, the energy expressed in watts · second can be easily calculated by multiplying the volume to be removed by the specific energy for certain cutting conditions.

Results and discussion

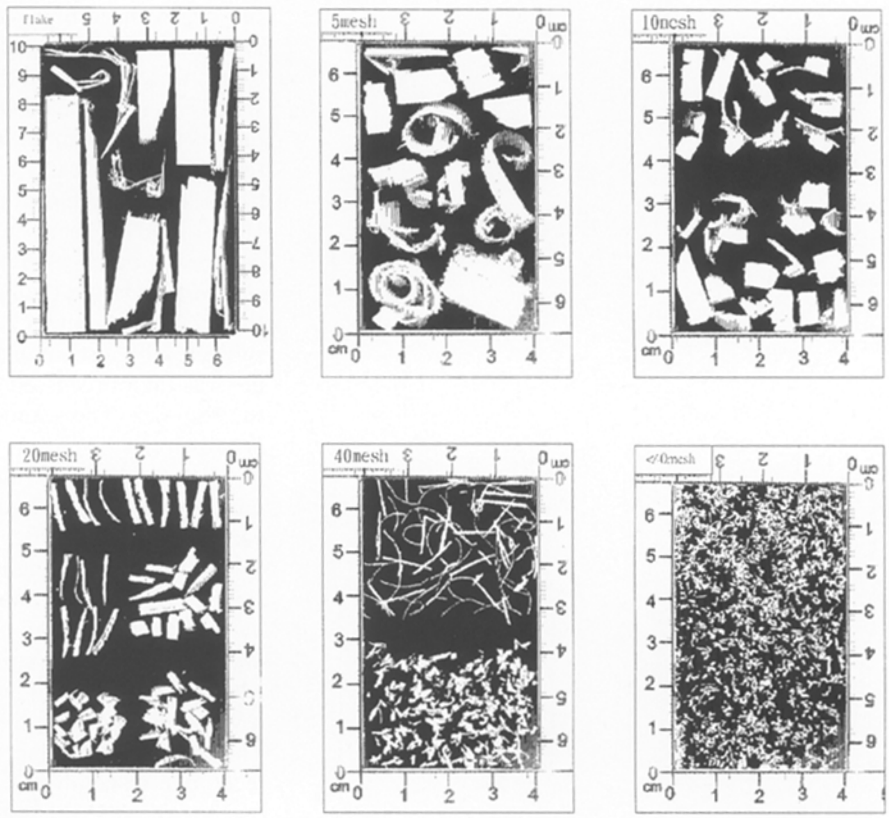
Chip classification

According to Franz's study,[8] the wood chip produced by orthogonal cutting parallel to the grain can be classified as Types I, II, and III. The chip produced from peripheral milling is somewhat different from that produced by orthogonal cutting.[9] Therefore, the chips collected in this study were sieved by steel screens of 5, 10, 20, and 40 mesh. The chips were then classified into six groups, shown in Fig. 3. The scale shown in Fig. 3 is in centimeters. It was found that the size variations in groups are quite large

Fig. 3. Types and dimension of chips. *L*, length; *W*, width; *T*, thickness

type / mm	Flake type	Splinter type 5mesh	Splinter type 10mesh	Flow type 20mesh	Flow type 40mesh	Granule type <40mesh
L	21.59–52.41 (32.25)*	8.27–18.93 (14.55)	4.04–10.32 (6.49)	10.92–11.97 (11.75)	1.62–5.20 (2.94)	0.74–3.14 (1.5)
W	8.42–11.94 (11.12)	7.92–13.1 (10.85)	3.52–11.27 (5.89)	2.10–2.69 (2.33)	0.67–1.65 (1.08)	0.26–0.86 (0.54)
T	0.81–2.95 (1.61)	0.83–2.80 (1.53)	0.32–1.42 (0.77)	0.22–0.34 (0.28)	0.03–0.11 (0.06)	0.03–0.09 (0.06)

*: Average values, Unit: mm



except for the chips of 20 mesh. It should be noted that the measuring directions of the chips were different for the three larger-size groups and the other three smaller-size groups. The lengthwise direction is coincident with the longitudinal direction for 5- and 10-mesh chips. However, the distance from end to end was measured as the chip length for the chips smaller than 20 or 40 mesh. The reason for this inconsistency was the change in chip geometry.

The six groups of chips are further classified into four categories according to chip type: flake type, splinter type (5 and 10 mesh), flow type (20 and 40 mesh), and granule type (smaller than 40 mesh). The flake-type chips are flat chips that could not pass through 5-mesh screen and were longer than 20 mm. The splinter-type chips are short block pieces and include curly chips. The flow-type chips are much more consistent with the ideal chip shown in Fig. 4.

Chip thickness analysis

During peripheral up-milling the cutting edge continually changes its cutting direction relative to the grain direction until it emerges at the workpiece surface. The chip thickness is constantly changing from a minute value to a maximum value as the cutting progresses, as shown in Fig. 4. The maximum thickness of the undeformed chip may be approximated by Eq. 1.[8]

$$t_{max} \doteq \frac{2F}{N \times Z}\sqrt{\frac{h}{D}\left(1 - \frac{h}{D}\right)} \qquad (1)$$

where t_{max} is the maximum undeformed chip thickness,
F is the feed speed,
N is the spindle speed (rpm),
Z is the number of cutting edges,

h is the depth of cutting, and
D is the tool diameter.

Table 1 shows the comparison between theoretical chip thickness calculated from Eq. 1 and the measured chip thickness for 20-mesh maple chips produced by a 0° helix angle cutter at various feed speeds and various cutting depths. It should be noted that the results for the various speeds were measured or calculated at a 4-mm cutting depth, and the results for the cutting depths were at 4800 mm/min. The inhomogeneous and anisotropic nature of wood always contributes complexity during machining. It should not be expected that the theoretical thickness of chips would match the measured thickness. The actual chips are always thicker than the predicted thicknesses at all feed speeds. The ratios of the measured thickness to the predicted thickness range from 1.5 for 4800 mm/min to 3.0 for 600 mm/min, showing that the ratio approaches 1.0 as the feed speed is increased. The observed split edge in the thickest part of the chip indicates that the actual thickness might even be thicker than the measured one. As far as the cutting depth is concerned, the measured/to the theoretical thickness ratio ranges from 1.8 for a cutting depth of 1 mm to 1.3 for a cutting depth of 6 mm. The feed speed seems to affect the thickness more than the cutting depth does when the aforementioned fact was considered.

The chip types shown in Fig. 3 were produced under almost all the tested cutting conditions. The exceptions, for instance, were the 10-mesh flat maple chips produced when the helix angle was 6° and the cutting depth was 1 mm; and the curly China fir chips in the 5-mesh category were produced when the feed speed was 600 mm/min and the cutting depth was less than 3 mm.

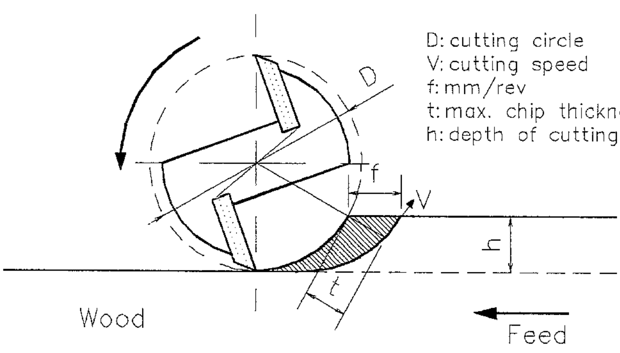


Fig. 4. Chip formation

The chip-type distribution on a weight basis for maple and China fir produced at a cutting depth of 4 mm at different feed speeds and with a feed speed of 4800 mm/min at different cutting depths for five helix angles are shown in Fig. 5. The portion of flow-type chips increased and that of the granule type decreased as the feed speed increased from 600 mm/min to 3600 mm/min for maple and China fir. The increase in flow-type chips is considered a positive factor of wood machining because it always results in better surface quality or less tool abrasion.[10]

The effect of the cutting depth is considered when feed speed is fixed at 4800 mm/min. The portion of flow-type chips increased and that of the flake- and splinter-type chips decreased with a decrease in cutting depth for both maple and China fir. Increased cutting depth thus increased machining efficiency. However, a cutting depth of 6 mm for both wood species resulted in larger portions of flake and splinter types than of the flow-type chips, indicating that the increased efficiency using the deep cut might be offset by the surface quality. There is no definite trend for the influence of helix angles on the distribution of chip types (Fig. 5).

Specific energy

Maple and China fir showed similar trends when the specific energy was related to the feed speed or to the cutting depth. Figure 6 shows that specific energy can be expressed as a negative power function of either the feed speed or the cutting depth for maple and China fir. The specific energy at feed speeds of 600 and 1200 mm/min was high, as shown in Fig. 6; it dropped dramatically when the feed speed approached 2400, 3600, and 4800 mm/min. The specific energy at cutting depths of 1 and 2 mm is high but converges at cutting depths of 3, 4, and 6 mm. No significant difference in the specific energy was found between the latter three feed speeds and between the latter three depths of cut. These results indicate that the high feed speed and the deep cut are more energy-economical because the specific energy is lower. In terms of the specific energy associated with different helix angles of the router bit, the difference in Chine fir is more significant than that in maple, as can be observed in Fig. 6.

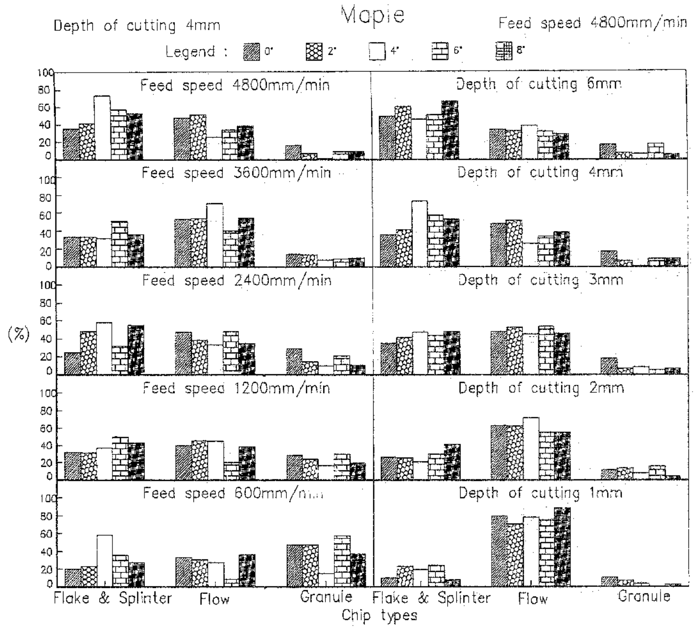
Conclusions

The effect of the helix angle on the chip type and distribution and the specific energy consumed per removed volume

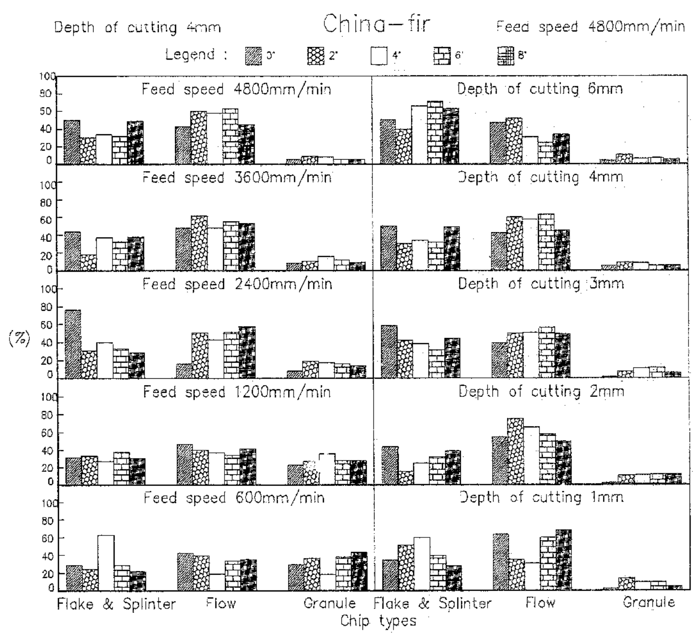
Table 1. Comparison between theoretical and measured chip thickness for 20-mesh maple chips produced by a 0-degree helical angle cutter

Chip thickness	Feed speed (mm/min)					Cutting depth (mm)				
(mm)	600	1200	2400	3600	4800	1	2	3	4	6
Theoretical	0.02	0.05	0.09	0.14	0.19	0.11	0.15	0.17	0.19	0.20
Measured	0.06	0.11	0.20	0.29	0.28	0.20	0.25	0.27	0.28	0.26
Measured/theoretical	3.0	2.2	2.2	2.1	1.5	1.8	1.7	1.6	1.5	1.3

Fig. 5. Chip types: distribution on weight basis while milling wood at various feed speeds and cutting depths



(a)



(b)

in conjunction with either the feed speed or the cutting depth was studied. The chip types could be distinguished into four groups – flake type, splinter type, flow type, granule type – according to chip sizes and shapes, respectively.

Regardless of the effect of the helix angle, the portion of flow-type chips increased and that of granule type decreased as the feed speed increased from 600 mm/min to 3600 mm/min. The proportion of flow-type chips increased and that of the flake and splinter types decreased with a decrease in cutting depth. The chip-type distribution and the specific energy at different feed speeds or different cutting depths seem not to be affected by the helix angle. The specific energy per volume removed can be expressed as a negative power function of either the feed speed or the cutting depth for maple and China fir with high correlation,

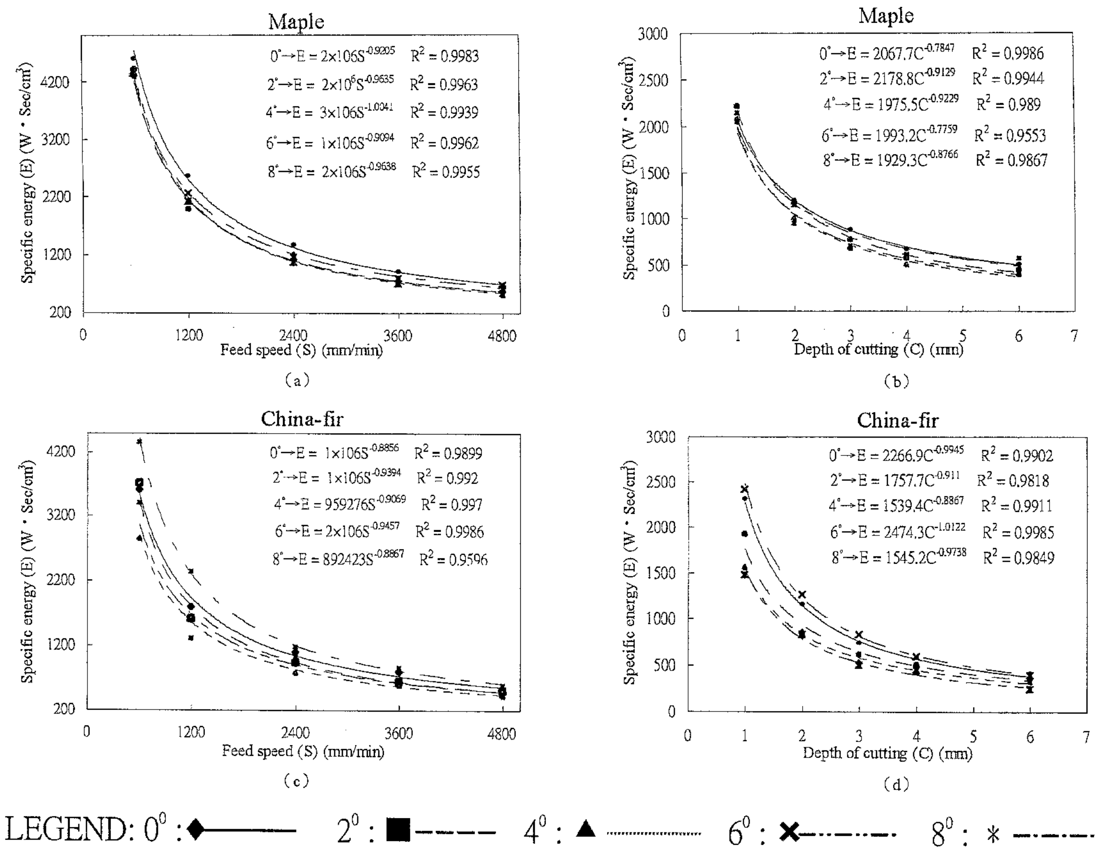


Fig. 6. Relations between feed speed, cutting depth, and specific energy while milling maple and China fir. *Diamonds*, 0°; *squares*, 2°; *triangles*, 4°; ×, 6°; *, 8°

indicating that the high feed speed and the deep cut are more energy-economical.

Acknowledgment This study was supported by a grant from the National Council of Science, Taiwan, Republic of China (grant number NSC88-2313-B-021-022).

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