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THE CHIPS GENERATED DURING UP MILLING AND DOWN MILLING OF PINE WOOD BY HELICAL ROUTER-BITS

Wayan Darmawan, Muhammad Azhari, Istie S. Rahayu
Dodi Nandika
Bogor Agricultural University, Faculty of Forestry
Department of Forest Products
Bogor, Indonesia

Rumanintya L. Putri
Islamic University of Balitar
Blitar, Indonesia

Satoru Nishio Malela
Pt Kanefusa, Japan

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ABSTRACT

Development of new helical edge router bits (helix angle 15°, 30°, 45°, and 60°) with a cutting circle diameter of 8 mm was studied. The purpose of the research work was to investigate chips formation and surface roughness characteristics in milling the pine wood by the straight and helical edge bits. The generated chips were classified in four types by sieving into spiral chip (5 mesh), flow chip (10 mesh), thin chip (30 mesh), and granule chip (< 30 mesh). The experimental results showed that the spiral chip was generated most often (on a weight percentage basis) by the bits during down milling process. More flow and thin chips were produced by the bits during up milling process. Better surface roughness was produced by bits during down milling compared to up milling. When the helix angle of the bits increased the amount of spiral and flow chips were increased and granule chip was reduced. The machined surface was better in roughness (lower Ra values) as the helix angle of the bits increased both in up milling and down milling processes.

KEYWORDS: Pine wood, straight and helical bits, up and down milling, chips type, surface roughness.

INTRODUCTION

Various approaches, including design of cutting tool, selection of the cutting tool material and application of machining conditions have been proposed for optimization and improvements in wood cutting operations. All of the approaches lead to much higher productivity, more economical cutting and reduction of the overall machining cost, in which resulted from better efficiency, stability, accuracy, and tool life during the cutting processes. Selection of cutting tool materials with surface coatings and surface modification was reported to increase tool life, decrease noise and improve surface quality (Darmawan et al. 2009, 2011, 2012). Among the approaches, design of cutting tool edge involved in the cutting processes should be very important. Today conventional designs of router bits with two or more straight cutting edges are widely used in the wood working industry for milling purposes. The manner of contact between this straight configuration of cutting edge and the work piece is a piecewise continuous curve. The straight cutting edge hits and intermittently engages the surface of the work piece during milling. This straight configuration leads to machined surface quality problem due to high splitting, compressing and damaging the wood cell structure near the surfaces.

One approach dealing with new design of helical edge has been being developed. Some research works and investigations have been done to find out the effect of helix angles of the helical cutting tool edge for wood cutting applications. Mostly the research works had been focused on energy behavior, cutting forces, dust emissions, and noise emissions with respect to the varied helix angles. The first general overview was investigation of helical edge design with helix angle up to 30° for wood chipping application (Pahlitzsch 1966, Pahlitzsch and Sommer 1966). They noted that an increase in the helix angle leads to an increase in the passive force (axial direction), however the vibration is reduced and the noise level is lowered. Noise reduction of more than 10 dB(A) is observed when cutting wood with helical edge milling tools of 18° helix angle (Heydt and Tuffentsammer 1979). It was reported in another study that helical edge design of a bit provides better surface quality compared to straight edge (Cyra et al. 1998). In milling wood against the grain, the greater the helical angle the smoother is the machined surface.

Research activities on the investigation of dust, chip, noise and force behaviors in planing operation using helical edge with helix angles between 0° to 10° were reported (Heisel and Weiss 1989, Heisel et al. 1993). It was noted in these studies that helix angles between 5° and 10° are considered to be useful in lowering the dust emissions. The increases in the helix angle from 0° to 8° leads to a significant decrease of noise emissions. New design of helical edge of milling cutter with extreme helix angles (45° to 85°) had been developed at the Technische Universität Dresden (Fischer et al. 2005, 2006) and their performance in planing wood was reported by Darmawan et al. (2011). The helical edges compared to the conventional edge of milling cutter provide better chip flow with nearly axial in direction and low flight velocity, which lead to easier handling and less power for suction system. Though the extreme helical edges (65°, 75°, 85° helix angles) generate slightly larger cutting power than the conventional edge (straight edge), however they are considerably much better in reduction of the cutting noise. The helical edge milling cutters are better in wear resistance, suffered less edge fractures, and produce better surface quality than the conventional edge milling cutter. The investigations have clearly confirmed that the helical edge is considered to be a valuable design to improve the performance of the conventional milling cutters for wood machining application. The results on the influence of the helix angle of bits (0° to 8o) on the chip type and distribution and the specific energy in conjunction with either the feed speed or the cutting depth were reported (Su and Wang 2002). The chip types are classified into four groups (flake type, splinter type, flow type, granule type) according to chip sizes and shapes, respectively. The proportion of flow-type chips increases and that of the flake and splinter types decreases 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.

CNC routers appeared to be the most popular woodworking machine. There are promising solutions dedicated to CNC operations in solid wood working (Cyra et al. 1996, Iskra and Hernandez 2010), which involve on-line feed rate adaptation based on monitoring of acoustic emission. Another approach involves experimental determination of optimal machining parameter for particular wood species, equipment and parts to be processed (Supadarattanawong and Rodkwan 2006). A mathematical model and computational procedure were also developed to allow for significant reduction of processing time of CNC milling operation of solid wood. These approaches for wood milling are essential to gain high productivity and to take full advantage of machine capabilities. However, 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. There may be some problems during such milling. For instance, very tiny chips in the air create a serious health hazard for workers. Because of smaller diameter of the router bit, the chips generated during milling will be quite different from that while planing or shaping operation and investigations on chip formation during milling wood are limited. Considering the fact that the previous research works on chip formations were done limited to the helix angles between 0° to 8° (Su and Wang 2002), therefore a new design of helical edge of router bits with larger helix angles (0° to 60°) has been developed in cooperation with Kanefusa Japan and their performance was tested in this research. Though the theoretical principle of the helical bits has a great promising to solve the outlined problems when milling wood, however investigations and tests should be performed for better description of the performance, and to prove the potential of the developed new helical bits in the near future. The purpose of this research work was to investigate the effect of helix angles on the chip formation, and surface roughness characteristics of the large helical edge of the bits in milling wood.

MATERIALS AND METHODS

Helical edge of router bits and work materials

The bits with helical edges were produced for the experiment in a standard production line by Kanefusa. The bits of K10 tungsten with helical edge design were 75 mm in total length, and 8 mm in cutting circle diameter. The bits consisted of two solid cutting edges with helix angles of 0° (straight edge), 15°, 30°, 45°, and 60° (Fig. 1). Other geometries of the helical bits are shown in Tab. 1.

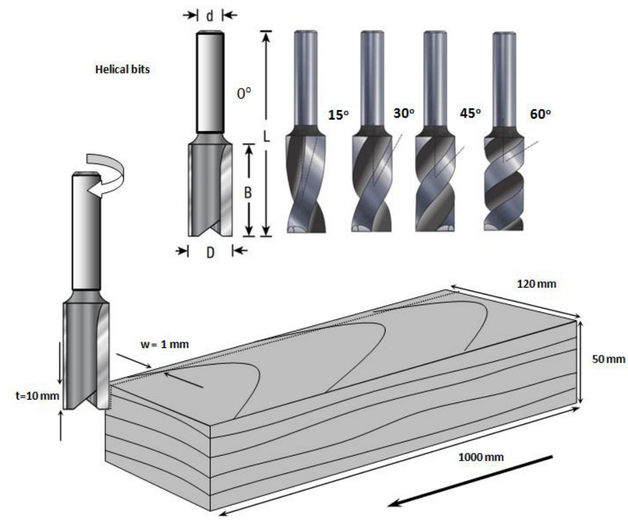


Fig. 1: Schematic diagram of the milling process and helical bits angles 15°, 30°, 45° and 60° for investigation.

Tab. 1: Specifications of conventional and helical bits for investigation.

Bit tool material	K10 Tungsten carbide
Hardness	63 HRC
Cutting circle diameter d	8 mm
Shank diameter D	8 mm
Number of cutting edge z	2
Total length of bit L	70 mm
Length of cut l	25 mm
Geometry of the edges :	
Helix angle	0° (straight edge),
	15°, 30°, 45°, 60°
Orthogonal rake angle	22°
Orthogonal clearance angle	15°

The wood species routed was pine (*Merkusii pine*) of 12 % in moisture content. Wood samples routed were in form of lumber in size of 50 x 150 x 1000 mm. Because pine wood contain a lot of tight knots, the lumber samples were chosen carefully and knots were not allowed in the surfaces of the lumber sample.

Milling test

Milling tests were set up on a commercial CNC router. Up-milling and down-milling processes were performed by setting the rotation of the router spindle in clockwise direction and by feeding the lumber samples in the proper direction with rotation of the spindle. The lumber samples were routed along the length on their side surfaces. The lumber samples were routed for five replications by keeping the same condition. Schematic diagram of the milling test is depicted in Fig. 2, and conditions of the milling are shown in Tab. 2.

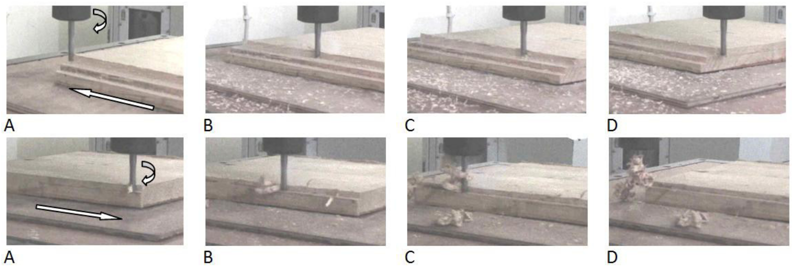


Fig. 2: View on chips formation during up milling (upper) and down milling (under) using straight edge bit at beginning of cut (A), middle of cut (B and C), and end of cut (D).

Tab. 2: Milling test conditions.

Adjusted parameters	Conditions for
Milling process	Up-milling and Down-milling
Bit revolution (rpm)	10000
Cutting speed ($m \cdot s^{-1}$)	4.2
Feed speed ($mm \cdot min^{-1}$)	2000
Depth of milling t (mm)	10
Width of milling w (mm)	1

Cutting speed of 4.2 $m \cdot s^{-1}$ was performed by setting the bit rotation of 10000 rpm and feed speed of the table of 2000 $mm \cdot min^{-1}$. The depth of cut (t) and width of cut (w) were determined to be 10 mm and 1 mm.

Chip flow and shape investigation

Investigations on chip flow and shape were carried out by mesh analysis of the formed chips and by digital camera monitoring. Digital video camera was focused on the distance of 1 m from the point of the cutting action. Video images were continuously taken during feeding of 5 lumber samples for each helical edge tested. The deposited chips on the table of the machine were collected and documented. The chips shapes in this work should be classified according to classification made by Su and Wang (2002). The collected chips were sieved by steel screens of 5 mesh (diameter of holes 11.32 mm), 10 mesh (diameter of holes 5.66 mm), and 30 mesh (diameter of holes 0.59 mm). The sieved chips were analyzed according to the chip type and the weight percentages of each chip type.

Surface quality measurement

The surface roughness tester SJ-210 was used to measure the roughness on the surfaces of the routed lumber. Samples for roughness measurement in the length of 50 mm were cut from the routed lumbers. Roughness values of Ra were measured across the grain of samples with a diamond tip radius of 5 µm. The tracing length was 15 mm and the cut off was 2.5 mm. The measuring force of the scanning arm on the surfaces was 4 mN, which did not significantly damage the surface according to the roughness tester SJ-210 user manual (Surftest Test SJ-210 2009). The 10 points of roughness measurements were diagonally marked on the surface of the samples. Measurements were made perpendicular to the fiber direction of the samples. Measurements were repeated whenever the stylus tip generated an error during the tests.

RESULTS AND DISCUSSION

Chips formation and flow

The straight bits tested produced different behaviors of chip flow between up milling (Fig. 2 upper) and down milling process (Fig. 2 under). In up milling the bits rotate against direction of feed. The chips width size are zero at initial cut, increase with feed and would be maximum at the end of feed. During up milling (Fig 2. 2A-D upper) the cutting chips were carried outward due to upward force by the tool bits. A large area of flow and high speed of flow were observed at beginning of cut up to end of cut. As a result the chips were tended to scatter around the cutting point and the table of the CNC machine (Fig. 2C-D upper). In down milling process the chip width size is maximum at start of cut and decreases with the feed, and would be zero at the end of feed. During down milling (Fig. 2A-D under) the cutting chips were carried outward due to downward force by the tool bits. It was observed that continuous chips were produced from beginning of cut up to end of cut. The continuous chips twisted upward (Fig. 2B under) and rolled up before fell at the end of the lumber sample (Fig. 2C-D under). The sector area of the continuous chips flow became smaller and the investigated speed of the continuous chip flow was decreased. This result gives an indication that the down milling process could create more-friendly environment compared to up milling process.

The same phenomenon was observed in milling using helical bits both for up milling and down milling processes (Fig. 3).

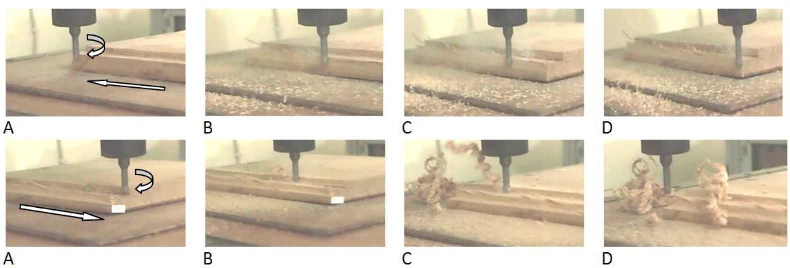
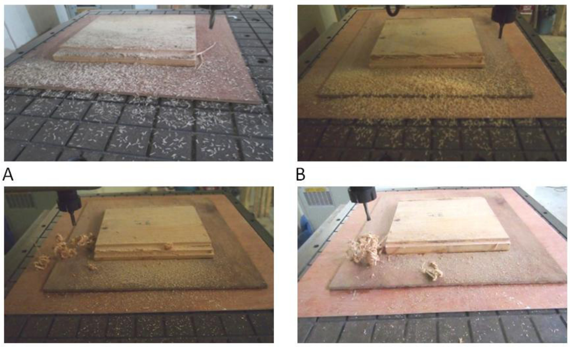


Fig. 3: View on chips formation during up milling (conventional milling) and down milling (climb milling) using helical edge bit (15° helix angle) at beginning of cut (A), middle of cut (B and C), and end of cut (D).

Completely severed chips were produced by the helical bits during up milling process (Fig. 3A-D upper), otherwise continuous chips were produced by the helical bits during down milling process (Fig. 3 A-D under). However, it was observed in up milling and down milling process that the chips flowed in a regular direction with lower area of flow and lower speed of flow, when the lumber samples were routed using the helical edges. With a further increases in helix angle, the chips left the cutting zone in an upwards direction, and the most regular way and the lowest speed were generated by using bits with 60° helix angle. Darmawan et al. (2011) observed that the chips move in a regular parabolic way during up milling using milling cutters with extreme edge helix angles (65°, 75°, and 85°). The chips flow velocity decrease rapidly when increasing the edge helix of the tool from 37 $m \cdot s^{-1}$ (helix angle 0°) to approximately 16 $m \cdot s^{-1}$ (helix angle 85°). Rudak et al. (2018) reported that at helix angle of bits les than 11°, the chips move in a plane perpendicular to the axis of the spindle rotation. When the helix angle of bit is 45°, the chips move upward in an angle of 22°. Speed of chips movement at 0° helix angle is about 26 $m \cdot s^{-1}$ and decreases to 16 $m \cdot s^{-1}$ at 60° helix angle.

The results in Fig. 4 show the chips produced and collected during up milling (upper) and down milling (under) using bit with helix angle of 15° (Fig. 4a,c) and 45° (Fig. 4b,d). During up milling with 45° (Fig. 4b) compared to 15° (Fig. 4a) helical bit, the chips were fallen in more regular way and deposited in a place at a distance closer to the cutting point. Darmawan et al. (2011) reported that the chips are collectively deposited in a place at a distance of about 30 cm to 50 cm away of the cutting point during planing lumber with milling cutter of 65°, 75°, and 85° helix angle. Down milling with higher helix angle of bits tended to produce continuous chips with less discontinuous chips compared to lower helix angle.



A B C D

Fig. 4: Comparison in behaviors of chips flight between helix angle 15° (a, c) and helix angle 45° (b, d) in up milling (upper) and down milling (under).

Fig. 4d give an indication that bit of 45° helix angle compared to 15° helix angle (Fig. 4c) produced less discontinuous chips (dusts) during cutting. Su and Wang (2002) reported that the number of small chips under the larger helix angle is reduced. It could be considered that a problem in the chips suction system during milling with a conventional bit could be completely solved by using bits with higher helix angles, in which a complete capture of dusts and chips with saving of energy consumption for the required suction system would be realized, as a proper hood would be placed around the sector of expected chip flow.

Chip shapes

Analysis on chip sizes generated during the milling showed that the bits produced some types and sizes of chips both in up-milling and down-milling processes (Fig. 5).

The collected chips in Fig. 5 were sieved for classification on the chip shapes, and the results are shown in Fig. 6. The chip shapes were determined as spiral chips (Fig. 6A) netted on 5 mesh sieve, flow chips (Fig. 6B) netted on 10 mesh sieve, thin chips (Fig. 6C) netted on 30 mesh sieve, and granule chips (Fig. 6D) passed on 30 mesh sieve. Spiral and granule chips were found in the down-milling process. The flow, thin and granule chips were found in up-milling process. Lower downward force imposed on the chips during down milling would result in incompletely severed chips through compression otherwise a higher upward force imposed on the chips during up milling would result in chip separation through tension perpendicular to the grain. Therefore longer chips or continuous chips were produced during down milling, and tended to rolled up to form spiral chips then fall at the edge of the lumber sample. The flow chip and thin chips produced during up milling matched the shape of the chips reported by Su and Wang (2002). During up milling and down milling parallel to grain, the initial cut is substantially parallel to grain, the subsequent cut has a considerable angle to the grain. The subsequent cuts may relate to the generation of granule chips during parallel to grain.

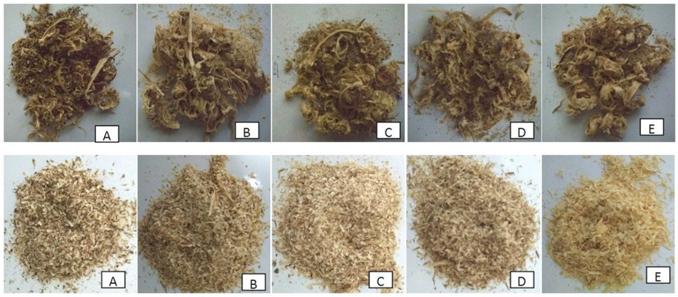


Fig. 5: The chips generated in down-milling (upper) and up-milling (under) using straight bit (A) and helical bits of 15° (B), 30° (C), 45° (D), and 60° (E).

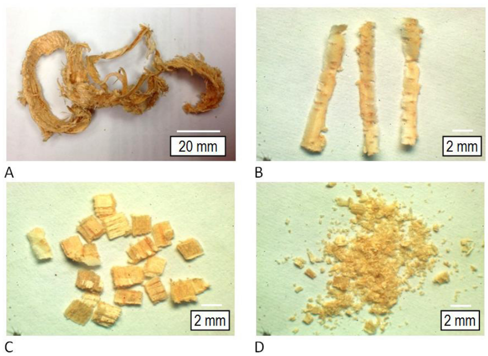


Fig. 6: Classification of the chips in 4 shapes: spiral (A), flow (B), thin (C) and granule (D).

The weight percentage distributions of different chip sizes sieved by the three screen sizes are shown in Tab. 3 and 4 for up milling and down milling process, respectively. The distributions were difference among the helix angle of bit.

Tab. 3: Classification of generated chips for up-milling process.

Helix angle of bits	Type of chips			
	Spiral	Flow	Thin	Granule
0	-	54	22	24
15	-	58	20	22
30	-	62	18	20
45	-	69	19	12
60	-	75	15	10

Tab. 4: Classification of generated chips for down-milling process.

Helix angle of bits	Type of chips			
	Spiral	Flow	Thin	Granule
0	78	-	-	22
15	80	-	-	20
30	85	-	-	15
45	88	-	-	12
60	92	-	-	8

Most of the chips generated in up milling process were flow type for almost all helix angles. Other chips were thin and granule chips. The increase in helix angle caused an increase in the percentage of flow chip and a decrease in the thin and granule chips (Tab. 3). The flow chip was 54% with 0° helix angle and 75% with 60° helix angle. The percentage of thin and granule chips for 0° helix angle was 22% and 24%, respectively, and for 60° helix angle was 15% and 10%, respectively (Tab. 3). The major shape of chips in 5 mesh sieve was the spiral chip (Fig. 6A) generated by all bits during down milling of the pine wood. The increase in helix angle caused an increase in the percentage of spiral chip. The spiral chip was 78% with 0o helix angle and 92% with 60° helix angle. The percentage of granule chips decreased from 22% at helix angle of 0° to 8% at the 60° helix angle (Tab. 4). The chips were generated by an intermittent engagement of the straight bit during milling in which the chips could be torn easily. Therefore, the chips obtained from the straight bit would contain larger percentage of smaller chips (thin and granule chips) than those produced by the helical bits. When using cutting edges with the helical configuration, the cutting edge penetrated gradually into the lumber samples with a step-wise force increase, which resulted in less granule chips. Burek et al. (2017) and Izamshah et al. (2013) reported that when cutting edges engaged the surface of the work piece gradually, the resultant cutting forces will be lower, the tools will be always under contact, stability will be improved, vibration will be reduced and the required machine power during the milling operation will be lowered.

Surface roughness

Machined surface roughness of various tree species has been investigated. Malkocoglu (2007) investigated planing properties and surface roughness of Scots pine (*Pinus sylvestris* L). Hiziroglu (2013) determined surface roughness in the sanding of pine (*Pinus strobus*), borneo camphor (*Dryobalanops* spp.) and meranti (*Shorea* spp). Zhong et al. (2013) evaluated surface roughness in various commercially produced composite panels including particleboard, medium density fiber board (MDF), and plywood in addition to ten different solid wood species which are commonly used in furniture production. Producing proper surface finish is an important part in the wood machining processes. The final surface roughness of lumber is considered as the sum of independent effects of geometry of tool, linear speed and feed rate, and wood characteristics. Geometry of tool, such as tool edge helix angle that is important in producing surface roughness, could be set-up in this experiment. Fig. 7 shows the effect of helix angle of bits on machined surface roughness for up milling and down milling process.

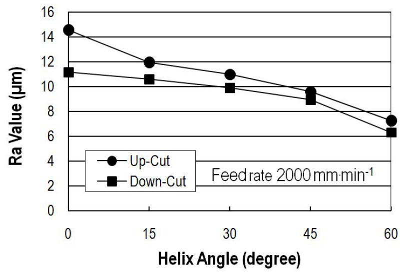


Fig. 7: The behavior of Ra values with helical edge of bits in up milling and down milling process.

The machined surface roughness for up milling process was higher than that for down milling process. The cutting forces in up milling are generally higher than in down milling. In down milling process the load from the cutting edge would be reduced, leaves a better surface finish. The higher in force and excessive compression may produce material crushing at the surface and deteriorate surface finish in up milling. Guo et al. (2015) stated that maximum negative force has great impact in machined surface roughness. Machined surface roughness increased with the increase of the maximum negative force. Another study revealed that the down milling process is better for workshop application than the up milling process because up milling process due to higher periodic cutting force is considered to be more damaging to the surface (Ozoegwu et al. 2013). The effect of chip type on surface finish could be also important in determining the surface roughness. The continuous chips generated during down milling process (Fig. 5) indicate that steady cutting conditions existed hence better surface finish was obtained. The discontinuous chips in up milling process created force fluctuations which would originate greater marks on the machined surface.

It appears also from the result in Fig. 7 that the roughness of lumber (Ra) decreased with increasing in the helix angle of the bits. The straight cutting edge hit and intermittently engaged the surface of the work piece during milling lead to machined surface quality problem due to high splitting, compressing and damaging the wood cell structure near the surfaces. Among the helical edge bits, the 60° helix angle tended to produce the smoothes surfaces. Baowan et al. (2017) noted that the TiAlN-coated end mill with a high helix angle of 60° offers high-quality surface finish with long tool life time and will be more useful for dry milling of stainless steels. It could be considered that when using cutting edges with the helical configuration, the cutting edge penetrated gradually into the work piece with a step-wise force increase, reaching a maximum value that would be lower than that achieved with a straight cutting edge. This result confirms with the previous report, in which the increase in the helix angle of milling cutters during planing wood results in the decrease in the roughness of wood surface produced (Darmawan et al. 2011, Fernando de Moura and Hernández 2006). In another study Izamshah et al. (2014) noted that because of the use of the unique geometry of helical cutting edges, the chips are easily deformed and the resulting machined surfaces are flat and smooth.

CONCLUSIONS

Both in up milling and down milling the helical edges compared to the straight edge of router bit provide better chip flow and low flight velocity, which lead to easier handling. Severed chips were produced by the helical bits during up milling process otherwise continuous chips were produced by the helical bits during down milling process. The chip types could be distinguished into four groups (spiral, flow, thin, and granule type) according to chip sizes and shapes. The portion of spiral chip was the highest in down milling process and that of flow chip was highest in the up milling process. Both the spiral and flow chips increased and the granule chip decreased as the helix angle increased from 0o to 60o. The helical edge bits produce better surface quality than the straight edge bit. The increases in the helix angle cause the decrease in the roughness. The investigations have clearly confirmed that the helical edge is considered to be a valuable design to improve the performance of the straight edge for wood milling application.

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Wayan Darmawan*, Muhammad Azhari
Istie S Rahayu, Dodi Nandika
Bogor Agricultural University
Faculty of Forestry
Department of Forest Products
Bogor 16680
Indonesia
Phone +62-251-8621285/8628012
*Corresponding author: wayandar@indo.net.id

Rumanintya Lisaria Putri
Islamic University of Balitar
Blitar
Indonesia

Satoru Nishio Malela
Pt Kanefusa
Japan