回転鉋の切削に関する基礎的研究

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バージョン：

Fundamental Study on the Peripheral Milling Process of Planing Lumber

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Résumé

This study was conducted to provide fundamental information pertaining to lumber planing and such basic problems in peripheral milling process of wood as the mechanics of chip formation, the machinability of wood and the cutting efficiency of multiple knife assembled on the periphery of cutter head were investigated.

I. Mechanics of chip formation

1. Factors affecting chip formation

In the begining of this investigation, the kinematics and geometry of both up-milling and down-milling were explained, and then the factors affecting chip formation during cutting were explored mathematically.

(1) In peripheral milling, the chip thickness (t) and the angle made between the tangential line to the trochoidal path taken by a knife tip and the one to the cutting circle (δ in Fig. 1. 2) are continoustly changing as a function of instantaeous depth of cut as expressed by Equation (1. 3) and (1. 9). Furthermore, in the case of wood-cutting, the relative cutting direction of a knife tip to the grain direction of wood being machined (η in Fig. 1. 5) varies continoustly along the travelling path of a knife tip as expressed by Equation (1. 8). (2) t and η vary simultaneously in wide range during a knife engagement with the work piece and it is considered that the both factors will play an important role in chip formation. (3) Although δ is too small to controll the process of chip severance under normal cutting condition as indicated in Fig. 1. 6, it will have an important influence upon the cutting operation in the case of jointed knife, because the knife edge has no clearance to cutting circle and this zero clearance angle acts as the negative clearance angle of δ during cutting.

2. Analysis of chip formation

With the object of analyzing the process of chip removal from wood during cutting, the transient phenomena of chip formation which took place under various machining conditions of both up-milling and down-milling were taken photograph by a high speed motion picture camera. Eight series of cutting tests (Table 1. 1) were carried on the automatic feeding vertical type of jointer equiped with the cutter head of 7 in. diam.. The knife materials used were high speed steel SKH_3, the cutting angle $\theta_0=55^\circ$, the clearance angle $\alpha_0=15^\circ$, and the test specimens were flat sawn boards of EZOMATSU (*Picea jezoensis*), moisture content $\mu=11\sim12\%$.

(1) Photo. 1.1～1.10 are photographs enlarged from the motion picture films developed. The number in the square bracket at the side of each photograph indicates the order of successive frames of the film, and the theoretical value of t and η at any situation of knife tip presented in the photograph can be calculated by use of the frame number with the aid of analitical diagram on the trochoidal path of knife tip as illustrated in Fig. 1.7. (2) There are two distinguished phases in the chip formation of up-milling during a knife engagement with work piece. The first phase of which is that termed "Continuous flow type" as illustrated in Photo. 1.1 [0]～[2] and 1.2 [0]～[2], where, the chip is severed by the knife tip directly from the wood surface being formed and soon after goes up the knife face without failurs in itself, accordingly the resultant surface is best. The second phase of which is that termed "Splitting type" as illustrated in Photo. 1.1 [7]～[24] and 1.2 [2]～[16], where, the chip is severed along the wood grain by wedging action of knife, and the split develops ahead of the knife tip until the chip gives away as a cantilever beam. (3) There are three distinguished phases in the chip formation of down-milling during a knife engagement with the work piece. The first phase of which is that termed "Shear type". Photo. 1.9 [−32]～[−25] and 1.10 [−30]～[−18] show this type of chip formation. This type occurs in the case of cutting into the sloping grain of wood, especially in the special case such as the grin runs parallel to the diagonal shear stress line extending from the knife tip. The second phase of which is the above splitting type as illustrated in Photo. 1.9 [−17]～[−13] and 1.10 [−11]. The last phase of which is the above continuous flow type as illustrated in Photo. 1.9 [−7]～[1] and 1.10 [−1]～[1]. (4) The splitting type of chip formation will prove the most efficient means of removing excess wood and cause little wear on the cutting edge, but the split will lead to torn or chipped grain defects on the surface produced when it occurs near the lowest level of trochoidal path of the knife tip. By contraries, the continuous flow type of chip formation will be most profitable from the viewpoint of surface quality, but it will cause considarable knife wear since the cutting edge is working at all times. Accordingly, it is desirable to arrange the machining factors affecting chip formation so that the continuous flow type of chip formation may continue as long as the knife edge passes through the visible residual portion of the trochoidal path. These arrangement of the factors will be expressed by Equation (1.10). (5) The continuous flow chip is formed within the certain limits of t and η on the low part of the trochoidal path taken by knife tip, and the limiting values can be measured from the frame number of the motion photograph as above stated. The limiting values measured are shown in Fig. 1.9. In this figure the outside curve indicates the superior limits of the both factors in which this type of chip formation continues in the case of peripheral milling at 480 m/min. of cutting speed, but the inside curve indicates the one in the case of orthogonal cutting at 0.5 m/min. of cutting speed. This figure reveals that the limiting value at the high speed cutting is

extremely high as compared with the one at the statical cutting. This result as well as the following fact that the curliness of the chip removed from wood in peripheral milling varies with the cutting speed as shown in Photo. 1. 13 and Table 1. 2 denots that cutting speed will be a function of chip formation. But, to get more knowledge on the effect of cutting speed on chip formation further studies are expected.

II. Machinability of wood

1. Cutting forces

1.1. Measurement of cutting forces The purpose of this section is to clarify the effects of machining factors on the cutting forces in peripheral milling of wood.

Horizonal and vertical type of milling machine (Photo. 2. 1, Fig. 2. 1) were used for cutting tests and the torsion meter and load cell applying strain gauge were arranged on them so that the cutting forces were resolved into two components, i. e., the main cutting force and the auxiliary component acting vertically to the feeding direction. The diam. of the cutter head 7 in. and 4.5 in., $\theta_0=55°$ and 60°, $\alpha_0=15°$, SKH_3. Test material was flat sawn boards of EZOMATSU and Sitka spruce (*Picea sitchenses*), $u=11\sim12\%$. Feeding rate of work piece (F), depth of cut (a), knife expansion beyond the jib face (C) and width of land formed by jointing operation on the knife edge (w) were varied within wide range.

(1) Fig. 2. 2∼2. 3 illustrate examples of cutting force curves recorded by the oscillograph. (2) The relations of F and a to cutting forces are affected by the radious of cutting circle as shown in Fig. 2. 5∼6. (3) C is inversely related to the cutting force up to a certain critical value as shown in Fig. 2. 7. (4) w has a pronounced influence on the cutting forces, especially on the vertical component as presented in Table 2. 1.

1.2. Analysis of cutting force Cutting forces are the results of composite influence of numerous factors. In this section the effect of the principal factors affecting the variation of t and η along the trochoidal path taken by knife tip on the main cutting force was analyzed theoretically from the view point of the mechanics of chip formation, and furthermore the propriety of the special cutting froce based on maximum chip thickness was discussed from the result of theoretical solution by the aid of experimental data obtained in the former section.

(1) The theoretical solution for the composite effects of F, a and radious of cutting circle (R) is presented in Equation (2. 8), (2. 9). In this equation, P_U: Mean value of tangential cutting force component during a knife engagement with work piece per unit cutting width or mean value of the work done by a knife engagement per unit cutting width, the work is revealed by the area under the cutting force curve anginst time. k_{so}: Specific cutting force in the orthogonal cutting parallel to wood grain at the same cutting angle and cutting speed that used in the peripheral milling. $k_{so}=c\cdot t_M^{-\varepsilon}$. t_M: Max. chip thickness. $g.\ b$: The coefficient concerned with the mecha-

nical property of wood to be cut. (2) Fig. 2. 8 presents the difference between the specific cutting force used in the present analysis (k_{so}) and the usual specific cutting force (k_s) in relation to t_M. This result reveals that k_s is out of place in peripheral milling wood. Fig. 2. 10 shows an example of the relation between P_U and t_M according to the above equation, and in this case (Sitka spruce, $\theta_0=60°$, $\alpha_0=15°$, $u=12\%$), $k_{so}=0.23\ t_M^{-0.57}$.

2. Surface roughness

2.1. Surface roughness in the feeding direction In order to determine the effect of f on the roughness values, some cutting tests were carried out on both a single side planer having the cutter head of 5 in. diam. and the above automatic jointer under various value of f resulting from different combinations of feeding rate of work piece and r.p.m. of cutter head as shown in Table 2. 2, SKH_3, $\theta_0=55°\sim56°$, $\alpha_0=15°$. The test materials were air dried flat sawn boards of nine species as listed in Table 2. 3. After planing, the surface profiles of the test specimens were measured along the feeding direction by means of a stylus tracer. Dealing with the resultant profile pictures, the following three kinds of roughness values were measured by the procedure as depicted in Fig. 2. 12, that is, maximum roughness by means of peak to valley method for the sampling length 14 mm (H_{max}), depth of knife mark for its pitch (h_e), and the roughness height for small pitch (h_a, sampling length 0.67 mm) (1) Examples of the profile curves obtained are shown in Fig. 2. 15~16. (2) So far as the knife edge is sharp, h_e shows comparatively a good agreement with the theoretical value based upon the trochoidal path taken by knife tip as illustrated in Fig. 2. 15. (3) h_a, which can be regarded as primary roughness principally due to both the wood structure and the form of cell walls destroyed by cutting action, increases slightly with the increase of f as shown in Fig. 2. 16 (1). (4) H_{max} decreases with the decrease of f, but the decreasing rate of it gradually decreases, especially under a certain limit of f it becomes almost constant as shown in Fig. 2. 16 (2).

2.2 Surface roughness in the rectangular direction to the feeding With the intention of obtaining knowledge on the distinction between the substantial surface roughness of wood due to its structure and the secondary roughness due to the destroyed cell walls by cutting action of knife, the profiles of various wood surfaces planed with both sharp and dull knife were measured across the grain direction (the rectangular direction to the feeding). The test specimens were flat sawn boards of four wood species presented in Table 2. 3 ($u=10\sim12\%$). They were planed firstly by a carpenter's hand plane with a sharp knife edge, secondary by the above single side planer with sharp knife edges, thirdly by the same planer but with dull edges. Each surface obtained was measured for the profile curve by a stylus tracer. Dealing with the profile curve the frequency curve of the roughness value basing on the center line system for the sampling length of 0.13 mm was obtained.

The profile curves and the roughness frequency curves are shown by wood species in Fig. 2. 18～19. These results denote that in the case of carpenter's sharp knife, the remaining surface irregularities are almost all of the substantial roughness due to wood structure and the surface approaches a technically ideal smooth surface, whereas in the case of machine planer knife, especially in the case of dull knife edge, the surface texture is disturved by the cutting action.

2.3 Variation of the surface roughness with blunting of knife edge In order to clarify the variation of the surface roughness with the blunting of knife edge, the successive planing tests of lumber were carried out on the above single side planer and the surface produced were measured for the surface roughness at every intervals of some lineal length of the lumber planed.

(1) Fig. 2. 20 illustrates the variation of the profile curve in the feeding direction obtained by stylus tracer and Fig. 2. 3 shows the variation of the three roughness values ($H_{\max}$, h_e, h_a) with the lineal length of the lumber planed. As shown in these figurs, the depth of knife mark (h_e) becomes shallower as the blunting of knife deverops. The reason why that is as follows, at the begining of the engagement of dull knife edge with work piece in up-milling, the edge thrusts some quantities of fiber into the wood face instead of removing the theoretical thin chip from wood as schematically shown in Fig. 2. 22, and then the fibers at the portion will spring buck over the face. As the result, the lower portion of knife mark becomes to upheave.

(2) Photo. 2. 4 illustrates the surface profile pictures in the rectangular direction to the feeding by means of light section method. Fig. 2. 24 shows the variation of the maximum roughness value evaluated from the pictures with the lineal length of lumber planed, and these variation is closly related with the blunting progress of knife edge as shown in Fig. 2. 21. In the first period, the knife edge wears away from both the face and back side of the knife and the surface roughness increases rapidly. But in the second period, the edge becomes to resist more wear and eventually settles down at a more or less uniform rate of wear, and the roughness value keeps nearly at constant. As the blunting develops furthermore, the defacement of the edge de velops chiefly from the buck side, and increases in the negative clearance angle. In the last period, the cutting reaches a critical stage by the increasing of the negative clearance angle as shown in Fig. 2. 21.

III. Cutting effeciency of multiple knife assembled on cutter head

Wood milling machine such as the jointer, the planer and moulder has multiple knife arranged on the periphery of a cutter head, and in order to do satisfactory multiple knife work, all knife tip must be brought into the same cutting circle. The jointing operation of the knives will be efficacious to this, but it seems to have a tendency to impair the sharpness of knife edge and shorten their lives. The main purpose of this chapter is to make clear these effects of the jointing operation upon cutting efficiency of multiple knife.

1. Analysis on the effect of jointing error on the formation of knife mark

If all of knife tips are arranged on the same cutting circle without error, each knife mark made by the individual knife tip on the surface should be quite equal with one another. In practice however, some errors in the arrangement (jointing error) are inevitable, consequently the knife marks become more or less irregular in their width as schematically shown in Fig. 3. 1. The effect of jointing error on the irregularity in the width of knife mark can be presented by Equation (3. 6)′. This equation reveals that the minor difference in the radious of cutting circle of each knife tip causes considarable irregulatity of knife marks, and the degree of the irregulatity is affected by the radious of cutting circle and the feed per knife. The mutual relation of these factors in this equation is nomographically shown in Fig. 3. 2.

2. Experiments on jointing procedure of knife

The object of this section is to obtain some practical data on the accuracy in jointing knife.

The machine used was a single side planer having 5 in. diam. four-knife head, equiped with a disk type grinding and jointing device (Photo. 3. 3) and both high speed knives (SKH_2) and tungsten carbide knives (WH_{50}) were tested. After setting on the cutter head, these knives were jointed under the following gringing and honing conditions. The grinding wheels used were W.A., #46, K and D, #200, J.. The hones used were made from a diamond nib mounted on an aluminum shank. The grits of diamond were #200, #400, and the rotating speed of the head was varied from 1,560 r.p.m. to 6,120 r.p.m., sliding speed of the hone was 0.6 m/min. Cutting tests of lumber were made after the following three steps in jointing procedur, that is, grinding, preliminary honing and perfect honing. Here, preliminary honing means such jointing situation as allows the face of the hone to come in touch with full length of all knife edge. After each cutting test, the surface of lumber planed was measured for the width of knife mark (e_1, e_2, e_3, e_4 in Photo. 3. 4), and from the result the jointing errors in each step were evaluated.

(1) The deviations in the width of knife mark ($\varDelta e_1 \sim \varDelta e_4$) are 0.6~3.1 mm after grinding and 0.15~1.5 mm after perfect honing as shown in Fig. 3. 6. The difference in the rotation radious of the four knife tips ($\varDelta_1 \sim \varDelta_4$) are 10~75$\mu$ after grinding, 10~50μ after preliminaly honing, and 5~20μ after perfect honing as shown in Fig. 3. 7. (2) The edges of tungsten carbide knife are liable to cause chipping when it is honed by the bigger sized diamond grits while the cutter head is rotating at the higher speed as shown the edge-roughness of jointed knives in Photo. 3. 5.

3. Surface quality of lumber planed with jointed knives.

In order to make clear the effects of machining factors on the surface quality in planing lumber, some experimental works were undertaken.

The cutting tests were carried out on the above single side planer under various combinations of machining factors such as f, d, θ and w. The both kinds of knives SKH_3 and WH_{50} were used and these knives were jointed as above stated process. Test materials consisted of 100～600 rough lumbers of three kinds of soft-woods and seven hard-woods as listed in Table 3. 2. After being dried and pre-planed, these lumbers were cut into pieces about 10 cm wide by 50 cm long, and they were grouped into 1～6 groups at every species so that each group might have an equal number of the piece and furthermore be similar in rang of specific gravity and width of annual ring of the pieces included. After planing test, the pieces were examined for surface defects, and the percentages of defect-free pieces (Y) and defective pieces (D) were determined. And the effects of the maching factors upon the surface quality were assessed by Y and D.

(1) The effects of f, θ and d on the surface quality are summarized in Table 3. 3 ～3. 5. These results indicate that f and θ are the most critical factor in the surfacing of lumber. (2) The effects of w are shown in Fig. 3. 11. This results indicate that the wider the land becomes, the poorer the surface quality is, and the actual width of land that can be used in surfacing lumber depends on the wood species. (3) Table 3. 6 shows the comparison of cutting efficiency of high speed knives and tungsten carbide knives jointed. (4) Machining characteristics of the test materials relative to surface quality are summarized as follows. SUGI (*Cryptomeria japonica*), URAJIROMOMI (*Abies homolepis*), AKAMATSU (*Pinus desiflora*) : The former two species are susceptible to both woolly grain and torn grain, and furthermore raised grain easily occure on the pith side, but the last species can be surfaced with relatively less trouble than the other. AKAGASHI (*Quercus acuta*) : The most prominent defect is chipped grain caused by both spiral grain and wide ray on the surface, but the other defects seldom occur. MAKANBA (*Betula Maximowicziana*), MIZUNARA (*Quercus mongolica*), BUNA (*Fagus crenata*), YACHIDAMO (*Fraxinus mandshurica*) : The chief defect is chipped grain, but slight degree of fuzzy grain occur. SHINANOKI (*Tilia japonica*) : The common defects are both chipped and fuzzy grain, and fuzzy surface is liable to develop. DORONOKI (*Populus Maximowiczii*) : Deep corrugation with serious fuzzy grain easily develops on the surface and this species is one of the hardest wood to produce a good surface quality.

4. Effect of jointing operation on output from multiple knife

In order to compare the output from jointed knives with that from unjointed ones, and furthermore, to ascertain the effect of jointing operation on the life of the knife, some experimental works were undertaken.

Four sets of knives were prepared on a cutter head for the test (the one set was unjointed knives, the other sets were jointed knives which had different width of land each other). With each set of these knives one or two series of successive planing tests of lumber carried out on the above single side planer, and the percentage of defect free pieces (Y) were measured at every intervals of 0.5～1 km of lineal length of lumber planed. The output from each set of knives on the cutter head was estimated by the maximum lineal length of lumber planed before Y had fallen down below 10%, and the life of a knife on the cutter head was represented by the total length of actual travelling path of the knife edge in wood before the knife arrived at the above critical stage.

Get results are summarized in Table 3. 8, in this table, L_{OM}'; the maximum length of lumber planed by unjointed knives and in this case one knife cutting has been done regardless of the number of knives mounted on the cutter head at the low feed rate of 11.9 m/min. ($\bar{e}=2.61$ mm), L_M': the maximum length of lumber planed by jointed knives and in this case multiple knife work has been performed at the high feed rate of 50.2 m/min. ($\bar{e}=2.75$ mm), L_{OM}, L_M: the total travelling length of a jointed and an unjointed knife respectively. This table reveals that the life of a knife is shortened by jointing operation essentially, and that the output from the multiple knife jointed slightly is more than three times than that from unjointed knives, whereas the output from the multiple knife jointed heavily is no more than about one-third. Thus, the output from multiple knife is under the control of jointing operation. These effects of jointing operation can be expressed by Equation (3. 17).