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ORIGINAL ARTICLE

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Milling of wood and wood-based materials with a computerized numerically controlled router V: development of adaptive control grooving system corresponding to progression of tool wear

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Abstract A laser measuring instrument was installed in a computerized numerically controlled (CNC) router, and an automatic measurement system, which was developed in a previous study, was used to automatically measure the cutting edge profile of throw-away type straight bits without stopping the CNC router. In addition to the above-mentioned system, in this study, an adaptive control program based on experimental data was installed, and an adaptive control grooving system that improved machining accuracy and controlled the burr formation corresponding to the progression of tool wear under processing was developed. Verification experiments of this system were carried out. The main results obtained are summarized as follows: (1) the between-process method was adopted for this system, and three types of processing methods (type 1, 2, 3), which consisted of a combination of an up-milling surface and a down-milling surface after processing, were investigated; (2) from the results of verification experiments, type 2 and type 3 methods showed remarkable ability to improve the machining accuracy and control the burr formation; and (3) it was found that the system employing adaptive control processing corresponding to the progression of tool wear in grooving is very effective.

Key words CNC router · Adaptive control grooving system · Tool wear · Machining accuracy · Burr formation

Introduction

Recently, computerized numerically controlled (CNC) routers have been introduced into the production lines of precutting factories and have been used under demanding processing conditions with the aim of raising productivity. Therefore, tool wear of the router bit rapidly progresses and chipping frequently occurs, which greatly influences productivity and product quality. In order to confirm the cutting edge profile of the router bit under processing easily and automatically, the authors installed a laser measuring instrument[1] in a CNC router, and the cutting edge profile measuring system was developed.[2,3] The system was composed of a laser measuring instrument, a control personal computer (PC) for the CNC router, and a monitoring PC for the control of certain devices and for collecting sampling data. As a result, highly accurate automatic measurements of both the progression of tool wear and the cutting edge profile under processing were achieved. Many studies on tool wear monitoring have been conducted in the past,[4–11] but few studies on automatic measurement of the progression of tool wear or the cutting edge profile under processing have been conducted.

In addition to the above-mentioned system, the present study aimed to develop an adaptive control processing system not only to improve the machining accuracy, which deteriorates with increasing tool wear, but also to control the burr formation that occurs in grooving. That is, the design was based on experimental data on both the machining accuracy for grooving and side-milling of grooves and the effect of tool wear on burr formation obtained in previous studies.[12–14] As a result, a system that automatically optimizes the processing condition in grooving that corresponds to the progression of tool wear was developed. Thus, the adaptive control grooving system was constructed, and verification experiments of this system were carried out.

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Materials and methods

Cutting tool, experimental apparatus, and workpiece

A throw-away type straight bit with a single-edged blade having a cutting diameter of 10 mm was used.[2,3,12–14] The tip material was K05-grade cemented carbide and the edge angle was 55 degrees. The rake and clearance angles in the set were 22 and 13 degrees, respectively. Router bits in which the tool wear (edge recession) reached 20, 40, and 59 μm by continuous cutting of particleboard were prepared. In this test, these worn bits and a noncutting bit were used.

A three-axis control CNC router (Karatsu Iron Works, RT-1 CNC Router) was used in this study.[2,3,12–14] It had a maximum spindle speed of 400 rps, a maximum feed speed of 0.12 m/s, and a position accuracy within 0.001 mm.

The workpiece used in this test was medium-density fiberboard (MDF). All pieces were 90 mm long, 90 mm wide, and 12 mm thick. The mean moisture content was 8.5%, the mean specific gravity was 0.66, and the specific gravity at the face and core layers was 0.78 and 0.58, respectively.

Adaptive control process

In the monitoring of tool wear and chipping, there is generally an in-process method of monitoring under processing and a postprocess method of monitoring after processing. In a production line such as that in furniture factories, the number of parts that one machine processes in a day is more than several hundred. In this case, the operator stops the machine and visually inspects the tool wear and chipping at a set number of parts or process intervals. This type of tool monitoring is neither an in-process method nor a postprocess method. It is generally called a between-process method because it is performed between processes. The between-process method was adopted for this system. The tool wear was automatically measured between set process intervals, and the adaptive control process that determines the optimum processing condition from these measurements was constructed. Figure 1 shows the flow chart of this adaptive control process. This process is initiated at the beginning, and measures the tool wear automatically when reaching set intervals. From the obtained measurements, the optimum processing condition that improves the machining accuracy of grooving and decreases burr formation is determined based on the experimental data from previous studies.[12–14] Finally, the numerical controlled (NC) processing data is restructured based on this determined condition and the process resumes.

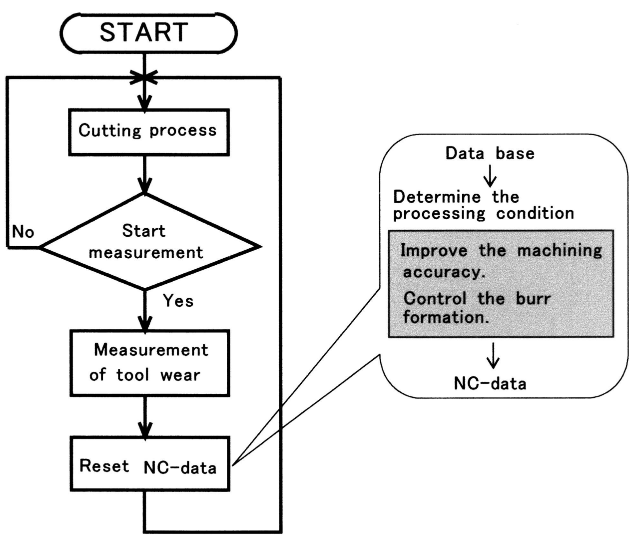

Fig. 1. Flow chart of the adaptive control process

Improvement method of machining accuracy

From the results of the previous study on the effect of tool wear on machining accuracy and burr formation,[12,14] cutting errors for MDF in grooving became larger with increasing tool wear and showed negative values. This is probably due to the decrease in the diameter of the cutting circle with progressive tool wear. Then the method for improving the machining accuracy in grooving was devised by processing the side-milling to the groove that is narrowed with tool wear. From the results of the previous study on the machining accuracy for side-milling of grooves,[13] it was determined that cutting error is minimized when both sides of the groove in side-milling consist of a combination of an up-milling surface and a down-milling surface. Next, considering the above-mentioned results, three types of processing method (types 1, 2, 3) that improve the machining accuracy were adopted.

Type 1

Figure 2 shows the type 1 processing method. After grooving, the bit was returned to the starting position of grooving. Setting the depth-of-cut to correspond to the amount of tool wear, the up-milling surface of the groove was cut by up-milling. Next, setting the depth-of-cut to correspond to the amount of tool wear, the down-milling surface of the groove was cut by down-milling.

Type 2

Figure 3 shows type 2 processing method. First, the bit was moved from the usual starting position of grooving to the down-milling direction of grooving by the amount of tool

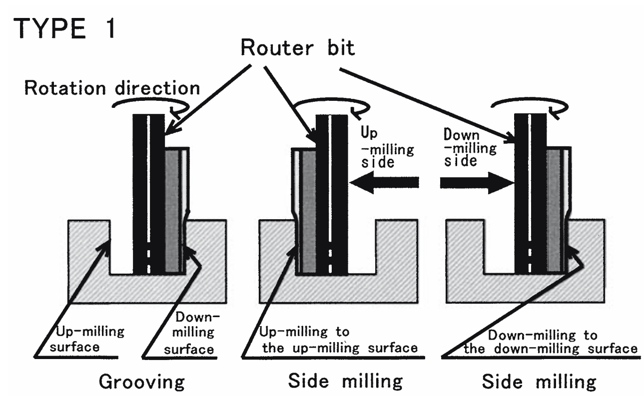

Fig. 2. Method of improving machining accuracy (type 1)

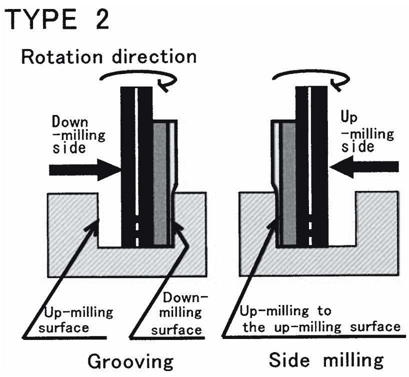

Fig. 3. Method of improving machining accuracy (type 2)

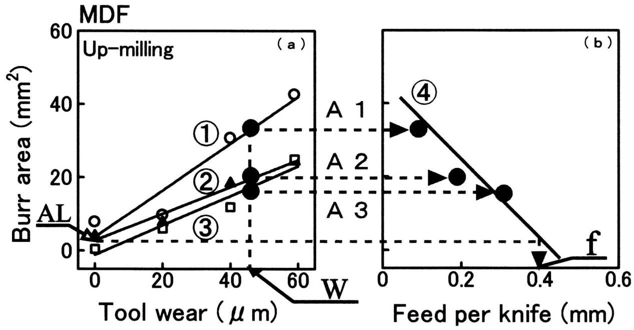

Fig. 5a,b. Method of determining a suitable feed per knife, **a** Relationship between burr area and tool wear and **b** relationship between burr area and feed per knife. See text for details

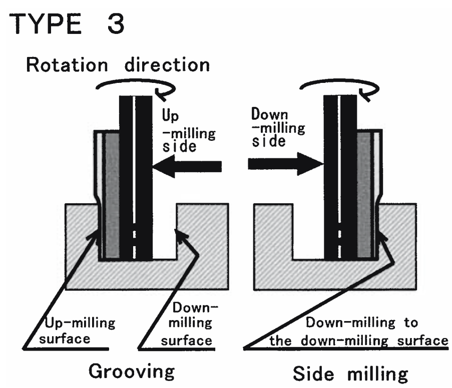

Fig. 4. Method of improving machining accuracy (type 3)

wear, and grooving was conducted. Next, the bit was returned to its initial position of grooving, and then, by setting the depth-of-cut to twice the amount of tool wear, the up-milling surface of the groove was cut by up-milling.

Type 3

Type 3 is a method that is opposite to type 2, as shown Fig. 4. First, the bit was moved from the usual starting position of grooving to the up-milling direction of grooving by the amount of tool wear, and the grooving was conducted. Next, the bit was returned to its initial position of grooving, and then, by setting the depth-of-cut to twice the amount of tool wear, the down-milling surface of the groove was cut by down-milling.

The three above-mentioned processing methods consist of a combination of an up-milling surface and a down-milling surface after processing. Therefore, the influence of the cutting error in the side-milling can be slight, and improvement of the machining accuracy will be expected.

Control method of burr formation

From the results of a previous study on the effect of tool wear on burr formation,[14] it was determined that the burr formation in grooving of MDF is remarkable on both the up-milling and down-milling sides of the groove, and this tendency becomes large with increasing tool wear and decreasing feed per knife. The tendency for burr formation was different depending on the amount of feed per knife, and it was suspected that enlarging the feed per knife according to increasing tool wear could control the burr formation. The method of determining the feed per knife so as to control burr formation, based on the amount of tool wear measured automatically, is explained below.

Based on the experimental data obtained in a previous study on the effect of tool wear on burr formation,[14] Fig. 5a shows the relationships between the burr area and tool wear in MDF obtained by the least squares method. Expressions ①, ②, and ③ are regressions at the feed per knife of 0.1, 0.2, and 0.3 mm, respectively. The correlation coefficients of expressions ①, ②, and ③ were larger than 0.93. Therefore, high correlation is confirmed between the burr area and tool wear. AL in Fig. 5 shows the average value of the burr area at feeds per knife of 0.1, 0.2, and 0.3 mm with a noncutting bit. The amount of tool wear with this system is automatically assumed to be W. When W is substituted for the expression, burr areas A1, A2, and A3 are obtained. Then, A1, A2, and A3 are converted into respective relationships between the burr area and the feed per knife by the least squares method as shown in Fig. 5b. The best feed per knife (f) for controlling burr formation is obtained by substituting AL for the expression ④. The correlation coefficient of expression ① was larger than 0.94 in any tool wear (W). Therefore, high correlation is confirmed between the burr area and the feed per knife.

Adaptive control program

In addition to the automatic measurement program for tool wear in the previous study,[2] the adaptive control program has new functions to determine processing methods (types 1, 2, 3), which improve the machining accuracy, and, to determine the feed per knife, control burr formation. Moreover, the measurement of tool wear to improve the measurement accuracy is increased to three locations, and the mean value of the measurements in the three locations is

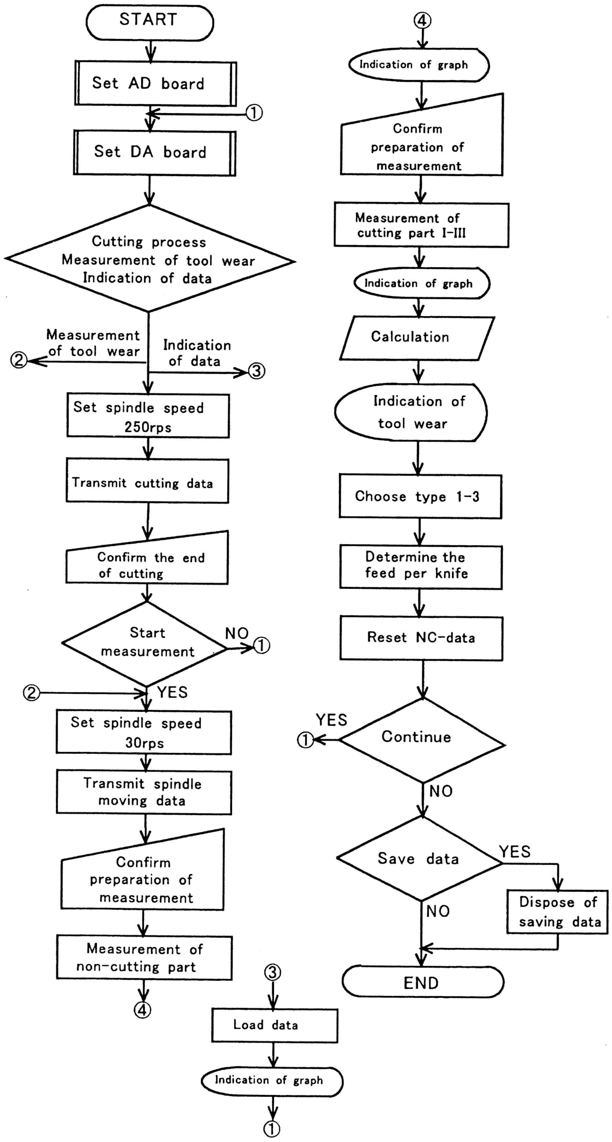

Fig. 6. Flow chart of the adaptive control program

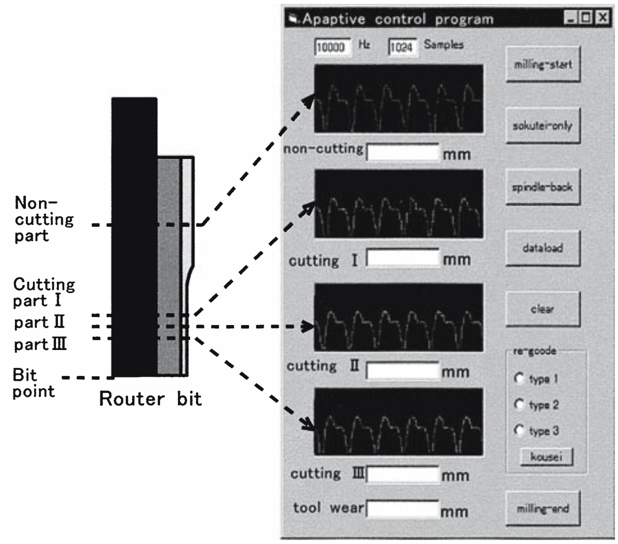

Fig. 7. Monitoring screen of the adaptive control program

Table 1. Grooving conditions used in this study

Spindle speed (rps)	Feed per knife (mm)	Depth of grove (mm)
250	0.1	5

assumed to be the bit diameter. The flow chart and the monitoring screen of the adaptive control program are shown in Figs. 6 and 7, respectively. The automatic measurement procedure for tool wear in this program is the same as the automatic measurement program of tool wear in the previous study.[2] Three processing methods (types 1, 2, 3) prepared beforehand are set to correspond to the tool wear that this system measured, and the feed per knife is decided based on the amount of tool wear. The numerical control (NC) data is restructured based on the set processing method and the feed per knife by the monitoring PC, and is transmitted to the control PC.

Verification experiment

A grooving test was conducted with worn router bits and an unused bit in an experiment to verify the proposed system. In addition, the usual grooving test was conducted for the sake of comparison. Usual grooving conditions for the test are listed in Table 1. In the grooving test with this system, the above-mentioned grooving conditions are set, and the feed per knife is changed in proportion to the amount of tool wear measured automatically. The sampling rate was set to 10 kHz and the sampling frequency was set to 1024 times. The laser light scanning position was set at three locations of 2, 2.5, and 3 mm from the bit point in the cutting region, and it was set at 8 mm from the bit point in the noncutting region. After the grooving test, the machining accuracy (the width of the groove) and the burr area at that time were measured by the same method as that used in the previous study.[12,14]

Results and discussion

Improvement of machining accuracy

Figure 8 shows the relationships between the cutting errors of both grooving tests and the tool wear. The increase of the cutting error with increasing tool wear in the usual grooving was remarkable. On the other hand, the cutting error of grooving with the proposed system was smaller than that of the usual grooving system for all three methods. Therefore, the improvement of the machining accuracy by the adaptive control process was verified. In particular, a tendency for remarkable improvement was shown in the cases of type 2

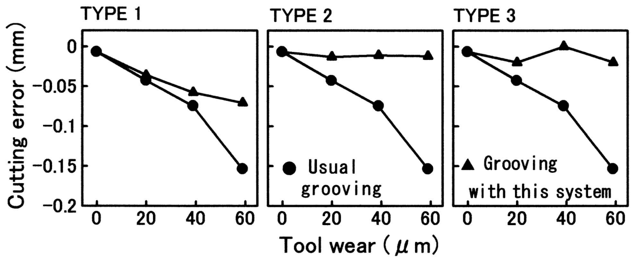

Fig. 8. Relationships between cutting errors and tool wear, for processing systems type 1, 2, and 3. *Circles*, data for normal grooving system; *triangles*, data for grooving with newly proposed system

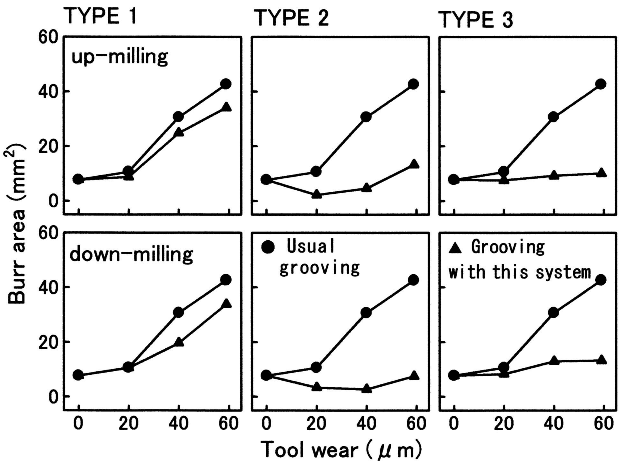

Fig. 9. Relationships between burr area errors and tool wear for processing systems type 1, 2, and 3 for up-milling (*upper panel*) and down-milling (*lower panel*)

and type 3 methods. The improvement effect of type 1 was small, which was thought to be due to the depth-of-cut setting being small when the side-milling is conducted and a slipping phenomenon results due to dullness of the tool edge, which increases with tool wear.

Controlling burr formation

Figure 9 shows the relationships between the burr area and tool wear for the different grooving tests. The increase in the burr area with increasing tool wear for normal grooving was remarkable. On the other hand, the burr area resulting from the adaptive control grooving system was smaller than that of normal grooving for all three methods. Therefore, control of the burr formation by the adaptive control processing was verified. In particular, a tendency for the burr formation to be controlled was shown in the cases of type 2 and type 3 methods (Fig. 10), whereas the controlling effect of type 1 method was small. It is considered that the same factor influencing the improvement of the machining accuracy also influenced control over burr formation.

From these results, it is clear that the adaptive control processing in grooving with this system based on the progression of tool wear is effective.

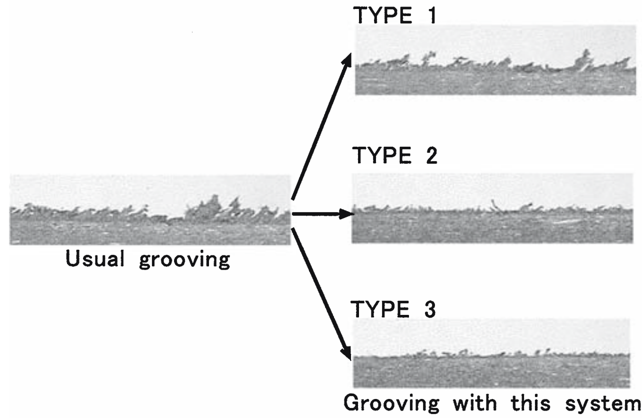

Fig. 10. Photographs of burring formed using normal grooving (*left*) and using the newly proposed system (type 1, 2, and 3)

Conclusions

In this study, an adaptive control grooving system was developed that improved machining accuracy, which normally deteriorates with increasing tool wear, and controlled the burr formation corresponding to the progression of tool wear under processing. The main results obtained can be summarized as follows:

1. The between-process method was adopted for this system, and three types of processing methods (type 1, 2, 3), which consisted of a combination of an up-milling surface and a down-milling surface after processing, were investigated.
2. From the result of the verification experiment, type 2 and type 3 methods showed remarkable abilities to improve the machining accuracy and control burr formation.
3. It was found that the system employing adaptive control processing that follows the progression of tool wear in grooving is very effective.

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