Paper:

Development of Innovative Intelligent Machine Tool Based on CAM-CNC Integration Concept – Adaptive Control Based on Predicted Cutting Force –

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[Received June 26, 2017; accepted January 14, 2019]

A new methodology to generate instruction commands for prompt machine control as a replacement for the previously prepared numerical control (NC) programs is developed to realize an innovative intelligent machine tool. This machine tool can eliminate NC program preparation, achieve cutting process control, reduce the production lead time, and realize an autonomous distributed factory. In this study, the innovative intelligent machine tool based on the computer-aided manufacturing-computer NC integrated concept is developed. The special feature of this system is to generate instruction commands in real time for prompt machine control instead of using NC programs. Digital Copy Milling, which is a digitized version of traditional copy milling, is realized by using only the computer-aided design model of the product. In this system, the cutting-force simulation is performed simultaneously with the real-time tool path generation. Then, the tool feed rate can be controlled according to the predicted cutting force. Therefore, both the improvement of the machining efficiency and the avoidance of machining problems can be achieved. The instantaneous cutting force model predicts the cutting force. In this system, the work material is represented by the voxel model, and the uncut chip thickness is calculated discretely from the number of voxels removed. Thus, it is possible to predict the cutting force in the case of non-uniform contact between the tool and the work material. In this study, a machining simulation is conducted to validate the proposed method. The results of the simulation show successful tool feed speed adaptation based on the predicted cutting force. The results also show the effective reduction of the machining time. A case study of a custom-made product for dental prosthetics is examined as a good application of both the proposed adaptive control and the Digital Copy Milling system. Through this method, it is possible to improve the machining efficiency and prevent tool breakage.

Keywords: intelligent machine tool, CAM-CNC integration, cutting-force simulation

1. Introduction

The automation of machining developed rapidly after the numerical control (NC) machine tool was introduced. The NC machine tool is operated by an NC program. However, numerous manual tasks to generate the NC program are required for users. On the other hand, the manufacturing system is changed drastically for manufacturing a wide variety of products in small quantities with changes in customer demand and the diversification of market requirements. Many mechanical parts with complicated shapes have been manufactured in the aerospace and medical industries, among others. Thus, the machining processes have faced the problem of the extensive time and effort required for generating NC programs using computer-aided manufacturing (CAM) systems. Although CAM systems have been used for generating NC programs, a high efficiency for reducing the preparation time of NC programs has not been realized. A conventional CAM system requires numerous manual tasks, such as the decision of the machining areas, sequence, and conditions. Studies have been performed on CAM systems to support the generation of NC programs [1–6]. However, an intelligent machine tool cannot be realized using the existing methods, because the machining operation is instructed by a part program or an NC program. Studies have been performed to automate the NC program generation by using only a computer-aided design (CAD) model. Hossain et al. proposed a method of voxel-based computer NC (CNC) code generation on a machine. They called the voxel-based CNC machining "Subtractive 3D printing" [7]. However, tool feed speed adaptation based on the predicted cutting force was not realized.

Our research group developed a methodology for generating instruction commands for prompt machine control instead of preparing NC programs. The system is called

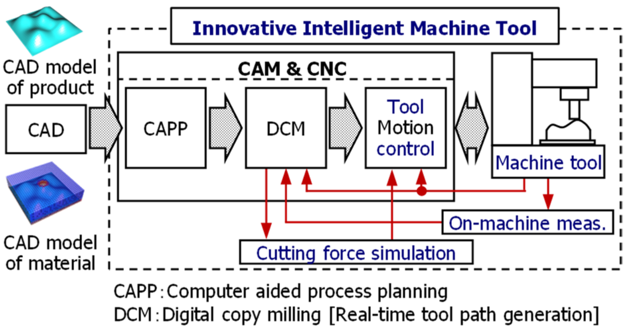


Fig. 1. CAM-CNC integration for the innovative intelligent machine tool.

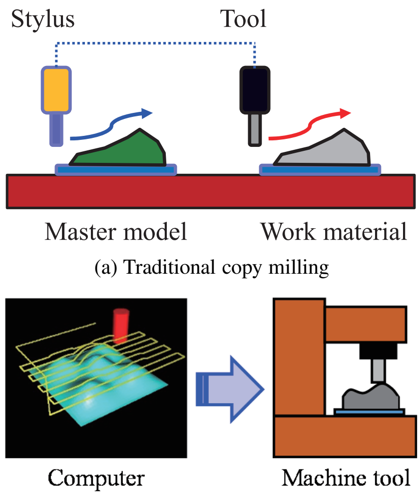


Fig. 2. Traditional copy milling and Digital Copy Milling.

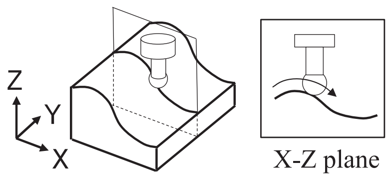


Fig. 3. Scanning-line mode in copy milling.

"Digital Copy Milling" and digitizes the principle of traditional copy milling [8–10]. The machine tool developed using this methodology can eliminate NC program preparation, control the cutting process, and reduce the production lead time for realizing autonomous machining operation and a distributed manufacturing system.

Figure 1 shows our new concept of CAM-CNC integration to realize an innovative intelligent machine tool. The new feature of this concept is that instruction commands for prompt machine control are generated in-process instead of the pre-prepared NC program. In this concept, the machining operation can be planned and performed automatically according to CAD models of the product and material without preparing any NC programs.

In this study, a new adaptive tool motion control method based on the predicted cutting force is proposed. In this method, instruction commands for prompt machine control are generated to control the feed speed in order to keep the predicted cutting force constant. To improve the productivity of the machining process and the quality of the machined surface, several adaptive control systems have been proposed and studied for real-time adjustment of the cutting parameters [11]. Researchers have designed machining operation control systems and realized an autonomous machine tool. For example, Altintas et al. achieved sensor-assisted milling operation using a hierarchical open-architecture multi-processor CNC system [12]. Mitsuishi et al. proposed a highly efficient machining system that maintains a stable machining state using multi-axis force information [13, 14]. However, in previous studies, CNC machine tools were generally driven by NC programs. Another method to control the feed speed according to the predicted cutting force with instruction commands for prompt machine control instead of preparing NC programs was proposed [15]. However, in that study, the feed speed was controlled at a constant rate of change of 10% instead of keeping the cutting force constant. When the predicted cutting force was larger than the cutting-force threshold, the feed rate decreased by 10%. When the predicted cutting force was smaller than cutting-force threshold, the feed rate increased by 10%. The present study proposes a new method to control the feed speed and keep the cutting force constant. Thus, the machining efficiency is improved, and machining trouble is avoided. A machining simulation is conducted to validate the proposed method.

2. Digital Copy Milling System

Digital Copy Milling digitizes the principle of traditional copy milling. In Digital Copy Milling, the tool path is calculated by a computer, and instruction commands for prompt machine control are generated. As shown in **Fig. 2**, traditional copy milling employs a tool, which behaves as a stylus that follows the master model in the real space. On the other hand, Digital Copy Milling can calculate the tool path in real time from the behavior of a virtual stylus, which follows the product CAD model corresponding to the master model in the virtual space.

In copy milling, there are different operation modes, such as scanning copy milling and contour copy milling. In this study, scanning copy milling is used, as shown in **Fig. 3**. Here, the displacement and movement direction of the stylus can be considered as a two-dimensional (2D) plane including the center axis and the movement axis of the stylus.

In traditional copy milling, scanning control is conducted according to the magnitude and direction of the displacement ε generated by the contact of the stylus with the master model in the real space. In Digital Copy Milling, scanning control is conducted according to the maximum interference between the virtual stylus and the

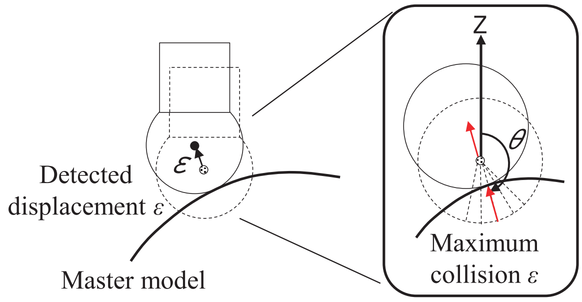


Fig. 4. Detection of maximum collision.

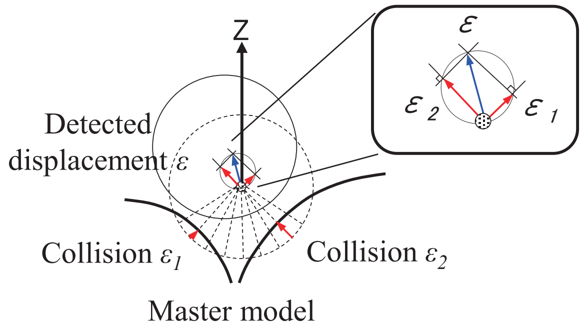


Fig. 5. Detection of resultant collision, where the stylus contacts two points on the workpiece.

virtual master model in the computer, which is regarded as the displacement ε. **Fig. 4** shows the relationship between the displacement of the stylus and the amount of interference. The amount of interference can be represented by the geometrical relationship between a circle of a stylus projected on the 2D plane and a surface of the master model. The angle $\theta_{\max}$, at which the interference amount is maximized, is calculated by calculating each angle θ according to the Z-axis. Then, the displacement direction and amount of the stylus ε are determined from the angle $\theta_{\max}$ [16].

When the stylus moves while copying on the master model, it contacts two points on the workpiece. In this case, the displacement direction and amount of the stylus ε can be calculated by adding the displacement direction and amount ε_1 and ε_2. As shown in **Fig. 5**, a circle circumscribing triangles that consist of two vectors ε_1 and ε_2 is drawn. The vector that passes through the center of the circle from the two-vector vertex represents the displacement direction and amount of the stylus ε.

Figure 6 shows the relationship among the vectors of the tangential feed velocity V_T, the normal feed velocity V_N, and the resultant feed velocity V. The tangential feed velocity V_T and the normal feed velocity V_N to the surface of the master model are calculated using Eqs. (1), (2), and (3).

$$|\varepsilon_d| = |\varepsilon| - \varepsilon_0, \quad (1)$$

$$|V_N| = G_N \cdot |\varepsilon_d|, \quad (2)$$

$$|V_T| = V_C - G_T \cdot |\varepsilon_d|. \quad (3)$$

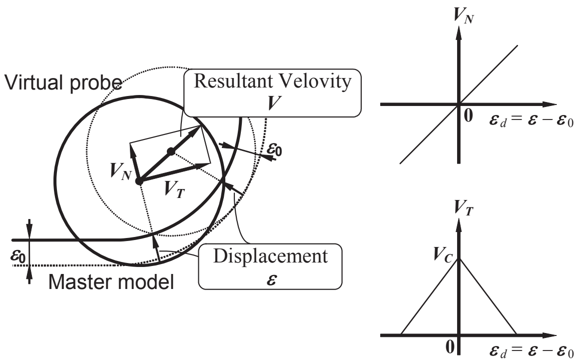


Fig. 6. Control principle in traditional copy milling.

In these equations, ε_d is the difference between the detected displacement ε and the target displacement ε_0, G_N is called the V_N gain and defines the relationship between ε_d and V_N, G_T is called the V_T gain and defines the relationship between ε_d and V_T, and V_C is the commanded feed velocity.

In Digital Copy Milling, the maximum collision ε between the geometric models of the virtual tracing probe and the virtual master model is used to calculate the resultant feed velocity V for controlling the tool motion. The virtual tracing probe is controlled to follow the virtual master model, and the cutting tool is controlled to follow the virtual tracing probe, as well as the traditional copy milling. The cutter location is calculated from the resultant feed velocity V at each control interval t (16 ms, which is limited by the specification of the CNC controllers). An NC machine tool is instructed by successive tiny NC blocks denoted as X, Y, Z, and F, which are converted from the cutter location and the resultant feed velocity V.

As previously mentioned, in Digital Copy Milling, the displacement direction and amount of the stylus ε can be calculated using the interference amount between the virtual stylus and the virtual master model in the computer. Therefore, instruction commands for prompt machine control can be generated.

3. Cutting-Force Simulation Referring to Voxel Model

The innovative intelligent machine tool developed in this study generates the tool path and predicts the cutting force simultaneously. Then, tool feed speed control based on the predicted cutting force to improve the machining efficiency and avoid machining trouble can be realized.

In this study, the instantaneous rigid-force model [17–20] is applied for the cutting-force simulation, although other models are widely used [21]. The instantaneous rigid-force model can accurately predict the cutting forces in end milling under the cutting mechanism described by the mathematical expression for the geometric relationship between the cutting edge and the workpiece. In this

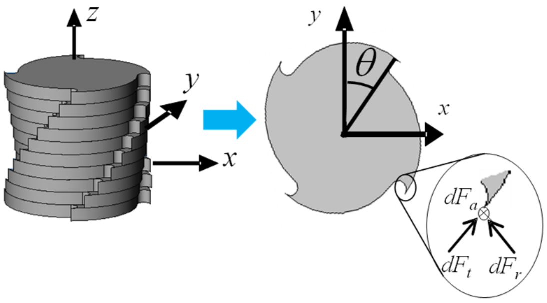


Fig. 7. Tool model and uncut chip thickness of the instantaneous rigid-force model.

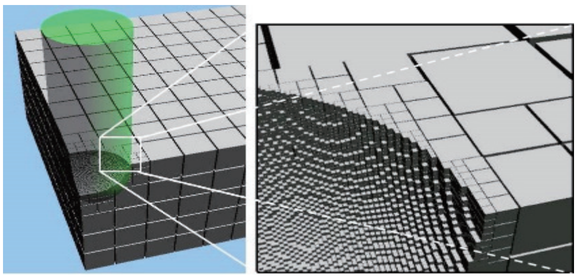


Fig. 8. Cutting-force prediction referring to the workpiece voxel model.

model, the cutting edge is divided into minute disk elements along the tool axis. The minute cutting force acting on each disk element is calculated as shown in **Fig. 7**. The total cutting force acting on the tool is then calculated by adding the minute cutting force acting on each disk element. The minute cutting forces acting on each disk element, such as the tangential force dF_t, the radial force dF_r, and the axial force dF_a, are described by the following equations.

$$dF_t = [K_{te} + K_{tc}h(\theta,z)]dz, \quad \ldots\ldots\ldots \quad (4)$$

$$dF_r = [K_{re} + K_{rc}h(\theta,z)]dz, \quad \ldots\ldots\ldots \quad (5)$$

$$dF_a = [K_{ae} + K_{ac}h(\theta,z)]dz. \quad \ldots\ldots\ldots \quad (6)$$

Here, K_{te}, K_{re}, K_{ae}, K_{tc}, K_{rc}, and K_{ac} are the cutting parameters; $h(\theta,z)$ is the uncut chip thickness; and dz is the thickness of the minute disk element. The cutting parameters can be obtained experimentally by measuring the cutting forces under various cutting conditions.

In the instantaneous rigid-force model, the cutting force is calculated from the uncut chip thickness $h(\theta,z)$. In this study, the work material is represented by the voxel model, as shown in **Fig. 8**, and the uncut chip thickness is calculated discretely from the number of voxels removed by the cutting edge for each feed per tooth. The advantage of the voxel model is that the uncut chip thickness can be calculated flexibly under the complex change of the machining shape and the uniform change of the contact state between the cutting edge and the workpiece.

In the extraction of voxels removed by the cutting edge for each feed per tooth, the computation time becomes long when the whole workpiece is represented by the smallest voxels. Therefore, the voxels in the tool bounding box are gradually divided and represented by the smallest voxels using the octree structure in order to reduce the computation time, as shown in **Fig. 9**.

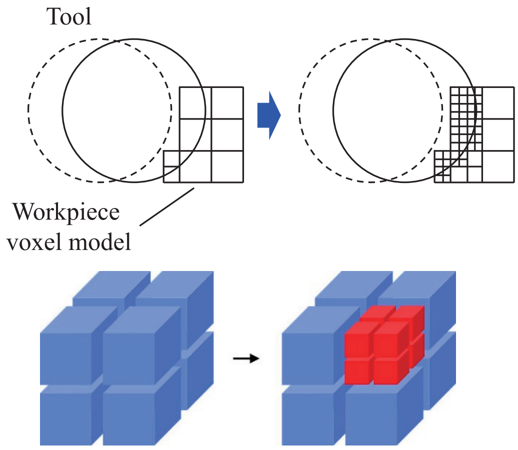


Fig. 9. Extraction of removal voxels represented by the hierarchical octree structure.

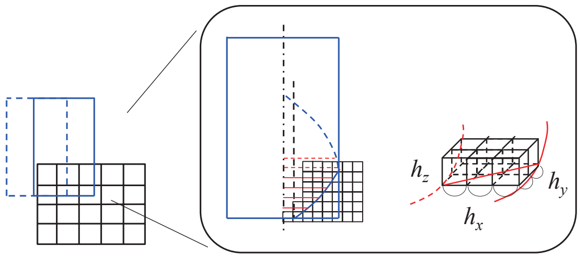


Fig. 10. Geometric relationship between the removal voxels and the axis components h_x, h_y, and h_z.

The uncut chip thickness $h(\theta,z)$ is described by the following equation with the x-axis component $h_x(\theta,z)$, the y-axis component $h_y(\theta,z)$, and the z-axis component $h_z(\theta,z)$.

$$h(\theta,z) = \sqrt{h_x(\theta,z)^2 + h_y(\theta,z)^2 + h_z(\theta,z)^2}. \quad . \quad (7)$$

The axis components $h_x(\theta,z)$, $h_y(\theta,z)$, and $h_z(\theta,z)$ are calculated discretely from the number of removal voxels, which are removed by the cutting edge, as shown in **Fig. 10**. The voxels, which exist along the vector connecting the tool axis to the cutting edge on the minute disk element, are extracted as the removal voxels. The axis components $h_x(\theta,z)$, $h_y(\theta,z)$, and $h_z(\theta,z)$ can be calculated as the product of the number of removal voxels and the size of the smallest voxel. Then, the uncut chip thickness $h(\theta,z)$ is calculated.

4. Tool Feed Speed Control Based on Predicted Cutting Force

In the existing automated machining, the cutting conditions and tool paths must be determined beforehand. Ad-

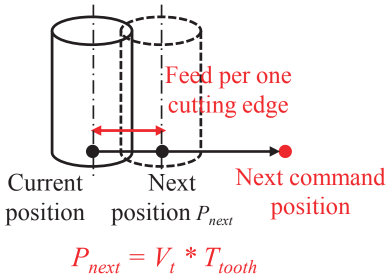


Fig. 11. Determination of the next tool position.

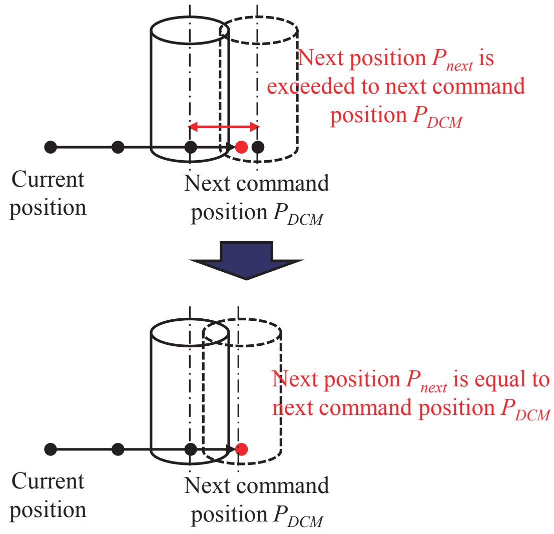


Fig. 12. Prevention of an error between the machining point and the command point.

ditionally, an NC program must be prepared from the cutting conditions and tool paths. The NC program cannot be modified during the automated machining, even if machining trouble occurs. Therefore, the NC program must be prepared carefully in order to avoid cutting trouble. The Digital Copy Milling system described in Section 2 generates instruction commands for prompt machine control instead of preparing NC programs. Therefore, the system has the advantage that the cutting conditions and tool paths can be flexibly changed during machining because it does not need to prepare an NC program beforehand. A new methodology to control the tool feed speed and keep the cutting force constant is proposed. In this methodology, the tool feed speed is controlled by not the measured cutting force but the predicted cutting force.

In the cutting-force simulation referring to the voxel model described in Section 3, the cutting force is predicted for every feed per tooth. In this study, the time of every feed per tooth is constant because the tool spindle speed is regarded as constant. The next position P_{next} can be determined from the multiplication of the cutting time for every feed per tooth T_{tooth} and the tool feed speed V_t on the vector from the current position to the next command position, which is calculated by the Digital Copy Milling system described in Section 2, as shown in **Fig. 11**. Then, the cutting force is predicted when the next position P_{next} is determined. The tool feed speed V_t is modified according to the predicted cutting force to keep the cutting force constant. When the next position P_{next} determined from the determined V_t is exceeded to the next command position P_{DCM}, the next position P_{next} is determined as equal to the next command position P_{DCM}, as shown in **Fig. 12**. The reason for this is to prevent an error between the machining point and the command point.

In the modification of the tool feed speed V_t, the cutting force $F_{V_{\max}}$ is calculated when the tool position is the next position P_{next} determined from the maximum tool feed speed $V_{\max}$. If the calculated cutting force $F_{V_{\max}}$ is smaller than the cutting-force threshold F_{th}, the tool feed speed V_t is determined as $V_{\max}$. On the other hand, if the calculated cutting force $F_{V_{\max}}$ is larger than the cutting-force threshold F_{th}, the tool feed speed V_t is determined by the following equation.

$$V_t = \frac{V_{\max} * F_{th}}{F_{V_{\max}}}. \quad (8)$$

In the instantaneous rigid-force model used for the cutting-force prediction, the magnitude of the cutting force is proportional to the uncut chip thickness. The uncut chip thickness $h(\theta, z)$ of each minute disk element is described as follows when the tool displacement is assumed as S_t and the tool rotation angle of the minute disk element is assumed as θ.

$$h = S_t * \sin\theta. \quad (9)$$

As indicated by Eq. (8), the tool feed speed V_t is calculated using the ratio of the cutting threshold F_{th} to the cutting force $F_{V_{\max}}$ determined using the maximum tool feed speed $V_{\max}$. In this study, the contact state between the tool and the workpiece during cutting with the maximum tool feed speed is considered to be the same as that with the tool feed speed V_t. Then, although the tool edge on the workpiece is different from the tool edge on the workpiece with a different tool feed speed, the difference of the uncut chip thickness is considered as negligible. Therefore, the tool feed speed can be determined using Eq. (8). The maximum configurable tool feed speed $V_{\max}$ is lower than the value for which the feed per tooth is equal to the tool radius. **Fig. 13** shows a flowchart for calculating the tool feed speed V_t, where the cutting force becomes equal to the cutting-force threshold F_{th}.

5. Case Study

A case study of end milling is examined to validate the proposed method. In the case study, the machining of the workpiece was conducted, as shown in **Fig. 14**. The cutting force decreases during machining under a constant tool feed speed. In this case study, machining with tool feed speed control using the proposed method to keep the cutting force constant (Pattern 1) and machining without tool feed speed control (Pattern 2) are compared. The

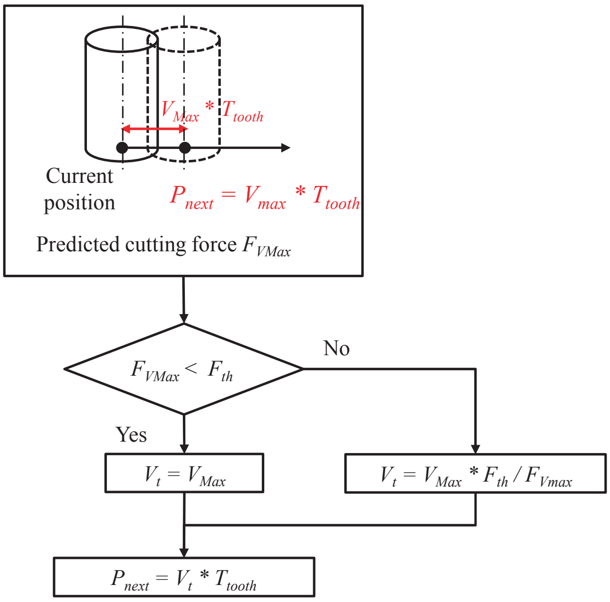


Fig. 13. Flowchart for calculating the tool feed speed V_t.

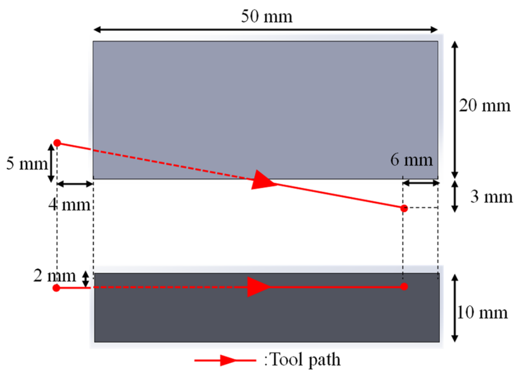


Fig. 14. Workpiece shape and tool path.

Table 1. Conditions of the cutting-force simulation for validating the adaptive control method.

Workpiece		A5052
Cutting tool	Tool type	ϕ10 square end mill
	Helix angle	30°
	Number of flutes	2
Cutting conditions	Cutting direction	Up cut
	Axial depth of cut	2 mm
	Spindle speed	2,000 min^{-1}
	Feed rate (initial)	480 mm/min
Disk element thickness		0.050 mm
Minimum voxel size		0.050 mm

conditions for the cutting-force simulation are presented in **Table 1**. For the cutting-force simulation, the cutting parameters for the instantaneous rigid-force model were determined in a preliminary experiment. For Pattern 1, the maximum tool feed speed V_{max} is 1,000 mm/min, and the cutting-force threshold F_{th} is 450 N.

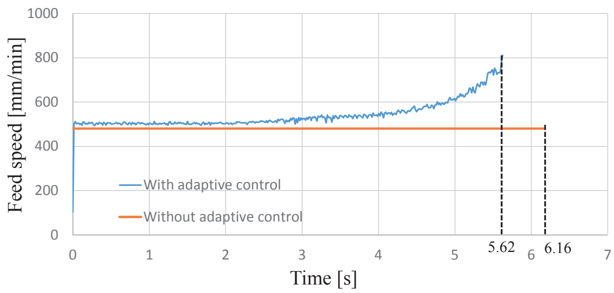
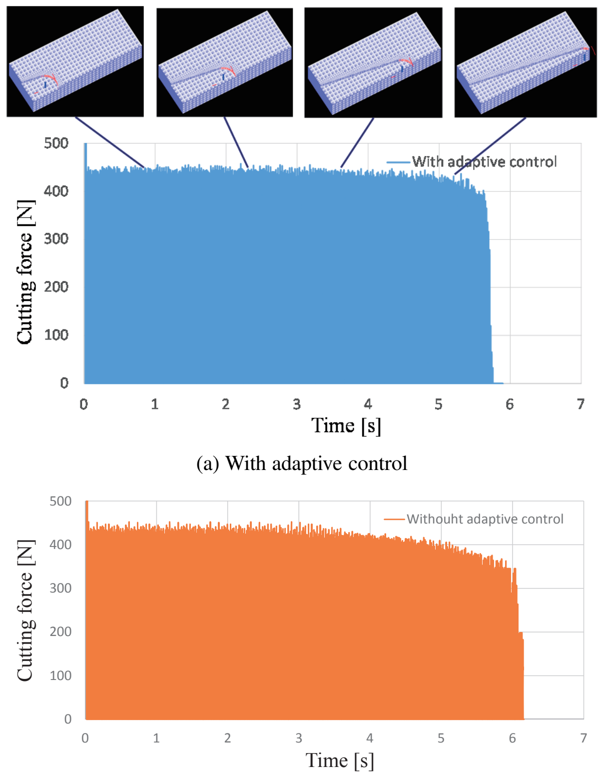


Fig. 15. Command tool feed speed with and without the tool feed speed control.



(a) With adaptive control

(b) Without adaptive control

Fig. 16. Comparison of the predicted cutting force with and without the tool feed speed control.

The results for the command tool feed speed are shown in **Fig. 15**. The results for the predicted cutting forces with and without tool feed speed control are compared in **Fig. 16**. **Fig. 15** shows that the tool feed speed was controlled to increase during the machining. The machining time with the tool feed speed control is shorter than that without the tool feed speed control. The results of this case study indicate that the proposed methodology can improve the machining efficiency and avoid machining trouble caused by overload.

Another case study of machining for dental prosthetics, as shown in **Fig. 17**, was conducted. In the field of dental treatment, the machining of dental prosthetics using dental CAD/CAM systems is rapidly becoming generalized because of the reduction of dental technicians and devel-

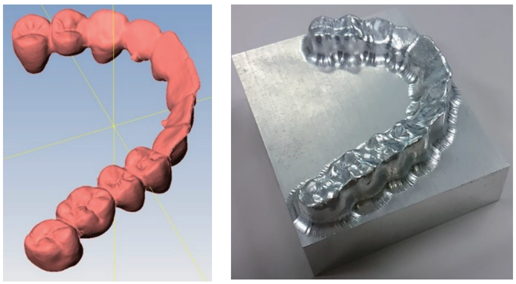


Fig. 17. Model of the dental prosthetics for the case study.

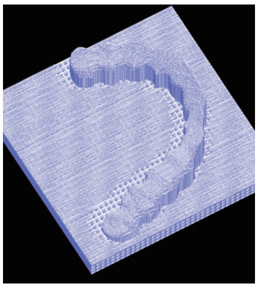


Fig. 18. Workpiece voxel model after rough machining.

opment of new materials such as ceramics [22]. However, the operation of CAD/CAM systems takes considerable time and effort from dental technicians, and it is difficult to generate a good NC program for the machining of dental prosthetics, because dental technicians are not familiar with machining and CAD/CAM operation. The Digital Copy Milling system developed by the authors has good potential to solve this problem.

There is no need to generate NC programs for machining using the Digital Copy Milling system. Custom-made products such as dental prosthetics are good applications of the Digital Copy Milling system. The proposed methodology has good performance for both improving the machining efficiency and avoiding machining trouble.

For the cutting-force simulation, the workpiece voxel model after rough machining by a ϕ4 square end mill was prepared, as shown in **Fig. 18**. The tool feed speed control was conducted during semi-finish machining of the workpiece after rough machining. The conditions of the cutting-force simulation are presented in **Table 2**. The maximum tool feed speed $V_{\max}$ was 2,000 mm/min, and the cutting-force threshold F_{th} was 80 N. The F_{th} was determined to prevent tool breakage.

The results for the predicted cutting force are shown in **Fig. 19**. The results for the commanded tool feed speed are shown in **Fig. 20**. As shown in **Fig. 19**, the predicted cutting force changed suddenly. The cutting force depends on the amount of cutting stock left by rough cutting. The sudden increase of the cutting force causes tool breakage. However, during most of the machining time, the cutting force is less than the F_{th} (80 N). To achieve a high machining efficiency and prevent tool breakage, it is necessary to adjust the tool feed speed to keep the cutting force less than the F_{th}.

Table 2. Conditions of the cutting simulation for dental prosthetics machining.

Workpiece		A5052
Cutting tool	Tool type	ϕ1 square end mill
	Helix angle	30°
	Number of flutes	2
Cutting conditions	Cutting direction	Up cut
	Axial depth of cut	0.08 mm
	Radial depth of cut	0.08 mm
	Spindle speed	2000 min^{-1}
	Feed rate (initial)	480 mm/min
Disk element thickness		0.050 mm
Minimum voxel size		0.050 mm

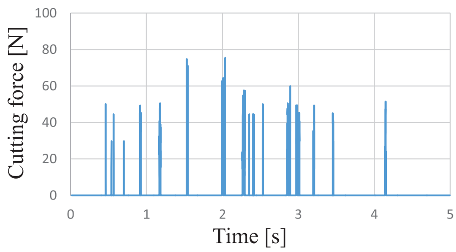


Fig. 19. Predicted cutting force in semi-finish cutting of dental prosthetics.

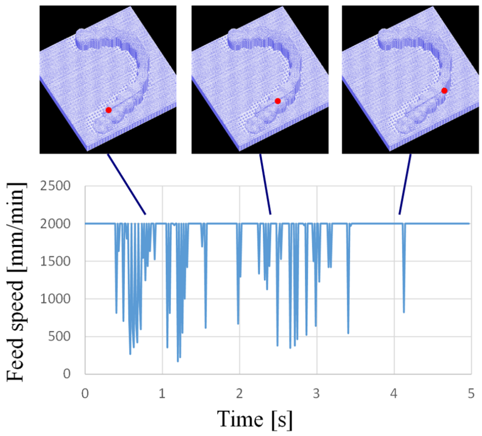


Fig. 20. Commanded feed speed under adaptive control for dental prosthetics.

As shown in **Fig. 20**, the commanded tool feed speed decreases suddenly when the predicted cutting force is larger than the F_{th}, to prevent tool breakage. Tool breakage of a small-diameter end mill can easily occur at a small cutting force. This means that adaptive control based on the measured cutting force is difficult, because the detection of a small cutting force is difficult. Therefore, the proposed adaptive control based on the predicted cutting force is effective for preventing tool breakage of a small-diameter end mill.

6. Conclusion

A new methodology for adaptive control of the tool feed speed based on the predicted cutting force is proposed. This methodology is integrated with the Digital Copy Milling system, which can generate tool paths in real time during machining operation. Our conclusions are summarized as follows.

1. A cutting-force simulator referring to a voxel model of the workpiece is developed. The advantage of using the voxel model is that the uncut chip thickness can be calculated flexibly under complex changes of the machining shape and uniform changes of the contact state between the cutting edge and the workpiece.

2. A case study of milling shows successful tool feed speed adaptation based on the predicted cutting force and effective reduction of the machining time.

3. A case study of a custom-made product for dental prosthetics shows that this is a good application of both the proposed adaptive control and the Digital Copy Milling system. It is possible to improve the machining efficiency and prevent tool breakage.

Acknowledgements

This work was partially supported by the Cross-ministerial Strategic Innovation Promotion Program (SIP) and JSPS KAKENHI (Grant Number JP17H03158).

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