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Paper:

Tool Motion Control Referring to Voxel Information of Removal Volume Voxel Model to Achieve Autonomous Milling Operation

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In order to achieve flexible and autonomous milling operation, a system called Digital Copy Milling (DCM) was developed in our previous studies. Additionally, tool motion control, in which the voxel information of the removal volume voxel model is referred to, is performed in DCM. In this study, a feed speed control function and tool posture control function are integrated with the DCM by referring to the feed speed and tool posture parameters stored in the voxel properties of the removal volume voxel model. It is assumed that these parameters change gradually as a diffusion phenomenon to automatically determine the voxel properties using a diffusion equation. In order to calculate the diffusion equation, the voxel in the removal volume corresponds to a calculation grid of the diffusion equation and not just to the storage of the feed speed and tool posture parameters. For experimental verification, the feed speed and tool posture parameters were automatically determined, and the tool motion was successfully controlled independent of the tool path generation to perform the milling operation.

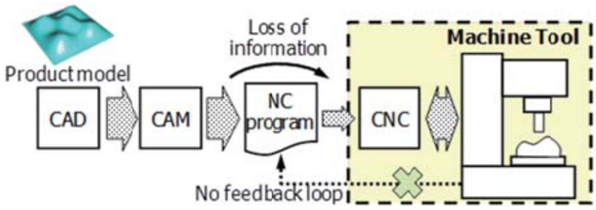
Keywords: digital copy milling (DCM), voxel model, removal volume, tool motion control, diffusion equation

1. Introduction

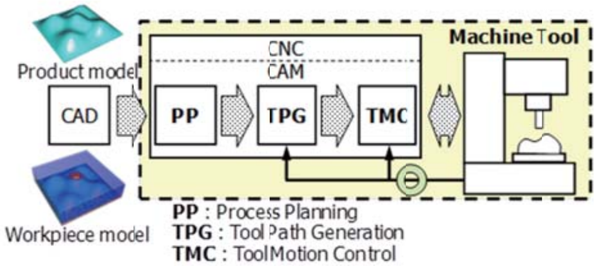
The machining sequence, tools, and cutting conditions of the conventional Numerical Control (NC) machine tools are all specified by an NC program, which has contributed to making machining operations highly automated, highly efficient, and highly accurate. However, all commands have to be determined in advance, and the machining sequence, tools, or cutting conditions cannot be changed during machining. Moriwaki [1] defined intelligent machine tools as "those which perform machining operations based on their own decision while conventional ones do machining operations as programmed in advance." The conventional NC program-controlled machines are not able to be made intelligent or autonomous. The NC program controls the motion of a machine tool accurately but does not control the machining process. Therefore, advanced functions such as control in accordance with the machining process or avoidance of machining troubles have not been realized. In this study, the authors developed a Digital Copy Milling (DCM) system that can generate a tool path and successively provide an instruction to a machine tool during milling operation based on a three-dimensional (3D) Computer-Aided Design (CAD) model of the product shape by not using conventional NC programs and have studied flexible and autonomous machine tools [2–4]. They also succeeded in developing an adaptive control system that can detect a cutting load during milling operation, change the tool path and the milling conditions, and avoid tool breakage [5].

In this study, a tool motion control function was added to the DCM system that could create a tool path based on a 3D CAD model of the product shape to improve the flexibility and autonomy of the machine tools. For tool motion control, a volume to be removed was expressed by a voxel model based on the 3D CAD model of the raw material shape, and the tool feed speed and the tool posture were controlled by referring to voxel information that were specified as attribution parameters of each voxel. A diffusion equation was used for the removal volume to automatically set the tool feed speed and tool posture to the attribution parameters of each voxel. A milling test was conducted with this tool motion control algorithm implemented to the DCM system to check its validity.

1. This paper is the full translation from the Transactions of the Japan Society of Mechanical Engineers Series C, Vol.79, No.808, pp. 4572-4581, 2013.



(a) Conventional NC machine tool



(b) Proposed autonomous and intelligent NC machine tool

Fig. 1. New concept to realize an autonomous and intelligent NC machine tool.

2. Autonomous and Intelligent NC Machine Tools with DCM

A conventional NC machine tool and the authors' proposed autonomous and intelligent NC machine tool are compared in **Fig. 1**. For the conventional machine tool in **Fig. 1(a)**, a Computer-Aided Manufacturing (CAM) operator creates an NC program, which only describes motion commands to the machine tool and does not transfer the product shape or other machining information to the machine tool. The machine tool only follows the commands described in the NC program and does not provide feedback of the machining state to the program. Therefore, advanced control according to the machining process cannot be realized. However, for the proposed machine tool in **Fig. 1(b)**, information about the product and raw material shapes are transferred to the machine tool, which then automatically designs the process plan, generates the tool paths, and controls the tool motion. With the CAM function integrated into the Computer Numerical Control (CNC), tool paths can be generated during milling operation to control the tool motion. An NC program is therefore not necessary, and the feedback of the cutting state is given to the system to change the tool paths and cutting conditions. In addition, the system can respond flexibly to a change in the production situation or production plan because the machine tool can automatically design machining operations.

The authors have developed a system called DCM that can give successive instructions while generating tool paths during milling operation based on a 3D CAD model of the product shape without using NC programs in the conventional way [2–5]. DCM is a new instruction method that digitizes a copy milling mechanism. In copy milling, a workpiece is machined by a tool, and the

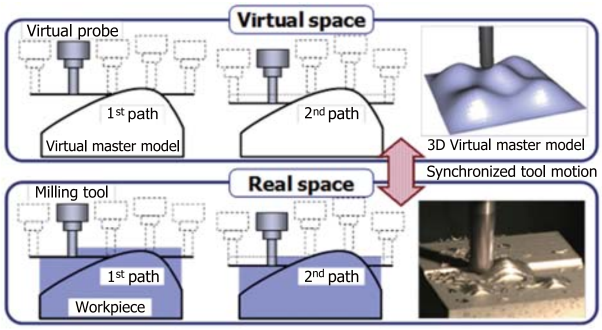


Fig. 2. Real-time tool path generation in Digital Copy Milling (DCM).

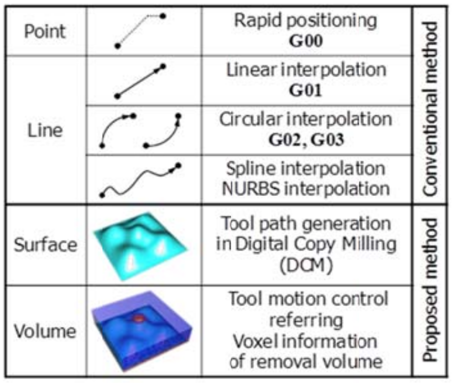


Fig. 3. Tool motion control in the conventional NC machine tool and DCM.

tool moves synchronously with a probe whose motion is manually controlled by an operator. In DCM, a virtual probe modeled in a computer, as shown in **Fig. 2**, generates tool paths in real time by automatically copying a 3D CAD model of the product shape and successively provides instructions about the tool position for the milling of the workpiece. Because it generates tool paths during the milling operation, it can change the cutting conditions such as cross-feed and depth of cut. This is the most distinguishing feature that is not found in the conventional machine tools that follow NC programs. Even when the milling conditions are changed during the milling operation, new tool paths are automatically generated according to the change of cutting conditions.

3. Tool Motion Control by Referring to Voxel Information

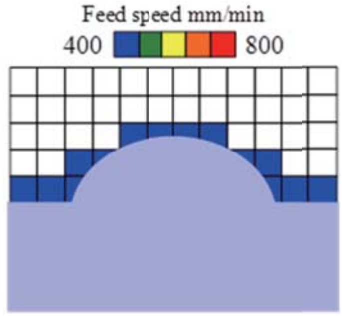
An NC program used in the conventional machine tools can only specify tool motion by "point" or "line," as shown in **Fig. 3**. Because the relative positions of the tool and workpiece are unknown to the machine tools, information is not enough to control the tool motion. The DCM generates tool paths based on a 3D CAD model (information about the "plane") of the product shape, but the plane information is not enough to identify the presence of the material or the difference between the milled area and the unmilled area. Therefore, the volume to be removed is expressed with a voxel model by referring to the 3D CAD model of the material shape, and the voxel information (about the "volume") is utilized to control the tool motion. The voxel model presents a 3D shape with a set of tiny cubes. This model can store information, which is referred to for tool motion control as the attribution parameters of each voxel that represents the removal volume. The information includes, for example, the distance from the product surface, the difference of the materials, tool feed speed, and tool posture. As shown in **Fig. 3**, compared to the conventional machine tools that follow NC programs, the proposed method can refer to a significantly larger amount of information and determine control commands for the tool feed speed or tool posture independent of the creation of a tool path during milling operation.

3.1. Setting the Voxel Information Using the Diffusion Equation

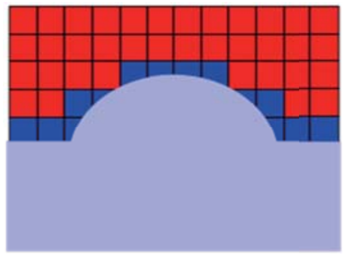
The present study focuses on the tool feed speed and tool posture controls to show some examples of tool motion control. In order to control the tool feed speed and tool posture according to the tool position in the removal volume, the reference information has to be set as the attribution parameters of each voxel that represents the removal volume. Although the tool feed speed and tool posture can be set locally, it is difficult to set them over the entire removal volume. Therefore, a method of determining the tool feed speed and tool posture over the entire removal volume is considered by using the tool feed speed and tool posture data designated locally. In particular, taking into account that the tool feed speed and tool posture would not change drastically during milling operation, a situation where the command values of these parameters were gradually changing is described as a diffusion phenomenon and a diffusion equation is used to determine the voxel attribution parameters for the entire removal volume. The diffusion phenomenon is a continuous change in a physical quantity; hence, the voxel attribution parameters for the entire removal volume can be determined continuously. The diffusion equation is expressed by the following differential equation that represents the diffusion of a physical quantity:

$$\frac{\partial f}{\partial t} = D\nabla^2 f \quad \text{. . . . . (1)}$$

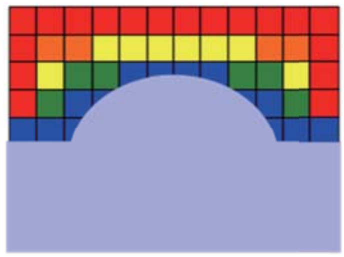
where t is the time, D is the diffusion coefficient, and f is a vector that represents the physical quantity. The physical quantity f is the tool feed speed or tool posture to be set as the attribution parameter of the voxel. In the numerical calculations, discretization was carried out with a difference method, and an explicit solution technique using the Euler method was employed to solve the equation. The voxel that represents the removal volume was used as a computational grid.



(a) Setting of boundary feed speed



(b) Initialization of Voxel properties



(c) Diffusion of Voxel properties

Fig. 4. Setting the voxel properties for feed speed control.

3.2. Setting the Tool Feed Speed

To improve milling accuracy and shorten milling time, it is necessary to make the tool feed speed slow in a removal volume near the product surface and fast in a removal volume far from the surface. Therefore, the tool feed speed of the voxel attribution parameter for the removal volume is set according to the distance from the product surface. In this case, the tool feed speed is controlled according to the distance from the product surface independent of the tool path. The voxel attribution parameter was set using the following steps:

1. Setting the lower limit of the tool feed speed as a boundary condition for a voxel near the product surface; refer to **Fig. 4(a)**.

   For each voxel that represents the removal volume, the attribution parameters of the tool feed speed in the x, y, and z directions are determined. First, a lower limit of the tool feed speed is determined as a boundary condition for the voxel in the removal volume that contains the product surface. In the present case, it was set to $V_{Lo} = 400$ mm/min.

2. Setting the upper limit of the tool feed speed as an initial condition for a voxel not near the product surface; refer to **Fig. 4(b)**.

   An upper limit of the tool feed speed is determined as an initial condition for the voxel in the removal volume that does not contain the product surface. In the present case, it was set to $V_{Hi} = 800$ mm/min.

3. Setting the voxel attribution parameters (tool feed speed) by using a diffusion equation; refer to **Fig. 4(c)**.

   On the basis of the voxel attribution parameters configured as the boundary and initial conditions, a diffusion equation is used to diffuse the parameter values. As a result, the tool feed speed that gradually changes over the entire removal volume can be set to the voxel attribution parameter. In the calculation, the tool feed speed is computed as a one-dimensional diffusion variable in each of the x, y, and z directions.

In the numerical calculations, the time is discretized by the forward difference method, and the space is discretized by the central difference method. The physical quantity on a spatial lattice site at the $(n+1)-$th time step, f_{ijk}^{n+1}, can be calculated from the one at the $n-$th time step, f_{ijk}^{n}, by the following equations:

- Tool feed speed in the x direction

$$f_{ijk}^{n+1} = f_{ijk}^{n} + \Delta t D \left(\frac{f_{i+1jk}^{n} - 2f_{ijk}^{n} + f_{i-1jk}^{n}}{\Delta x^2} \right) \quad (2)$$

- Tool feed speed in the y direction

$$f_{ijk}^{n+1} = f_{ijk}^{n} + \Delta t D \left(\frac{f_{ij+1k}^{n} - 2f_{ijk}^{n} + f_{ij-1k}^{n}}{\Delta y^2} \right) \quad (3)$$

- Tool feed speed in the z direction

$$f_{ijk}^{n+1} = f_{ijk}^{n} + \Delta t D \left(\frac{f_{ijk+1}^{n} - 2f_{ijk}^{n} + f_{ijk-1}^{n}}{\Delta z^2} \right) \quad (4)$$

where Δt is the time step; D is the diffusion coefficient; and Δx, Δy, and Δz are the lattice spacings (sizes of the voxel that represent the removal volume). Those parameters are set as $\Delta t = 0.1$ s, $D = 40$, and $\Delta x = \Delta y = \Delta z = 2$ mm. The numerical calculation could be terminated in the middle of the diffusion process, but the calculation was continued until the physical quantity on the lattice sites reached a stable state.

The tool feed speed, which is referred to for tool motion control, needs to be set for each of the x, y, and z directions. With the weight of a vector component in the tool feed direction, the tool feed speed can be appropriately calculated in accordance with the tool feed direction.

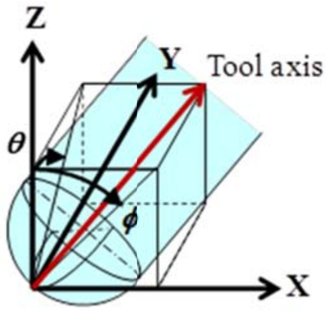


Fig. 5. Definition of the tool posture.

3.3. Setting the Tool Posture

In order to maintain the condition of the product surface in five-axis milling operations, it is necessary to maintain the relative postures of the product surface and tool. Therefore, the tool posture of the voxel attribution parameters for the removal volume is determined relative to the normal direction to the product surface.

By doing so, the tool posture can be controlled according to the tool position and not to the tool path. A ball end mill considered in this study, the tool posture was defined by an angle θ about the x axis and an angle ϕ about the y axis in the work coordinate system, as shown in **Fig. 5**. The voxel attribution parameters θ and ϕ were determined using the following steps:

1. Setting the normal direction to the product surface as a boundary condition for a voxel near the product surface; refer to **Fig. 6(a)**.

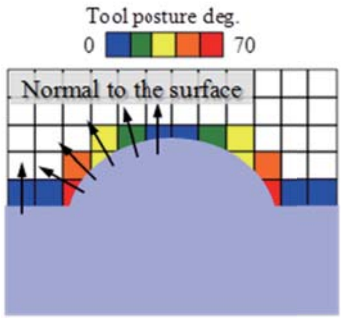
   For each voxel that represents the removal volume, the attribution parameters of the tool posture θ and ϕ are determined. It is assumed that the z axis of the tool is along the vector normal to the model surface in the milling operation of the product surface. The tool posture parameters θ and ϕ are then calculated from the normal vector and set as a boundary condition for the voxel that contains the product surface. In order to prevent excessive tilting of the tool, the tool posture parameters θ and ϕ are limited up to $\pm 70°$, but no measure is taken to avoid tool collision.

2. Setting the tool posture parameters $\theta = 0$ and $\phi = 0$ as the initial conditions for a voxel not near the product surface; refer to **Fig. 6(b)**.

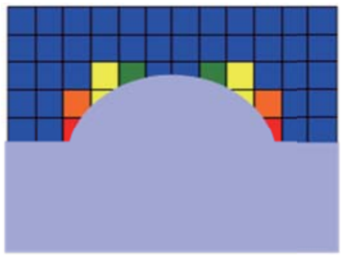
   The tool posture parameters $\theta = 0$ and $\phi = 0$ were set as initial conditions for a voxel in the removal volume that does not contain the product surface.

3. Setting the voxel attribution parameter (tool posture) by using a diffusion equation; refer to **Fig. 6(c)**.

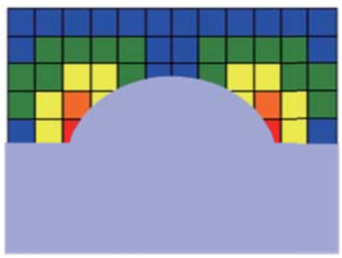
   On the basis of the voxel attribution parameters configured as the boundary and initial conditions, a diffusion equation is used to diffuse the parameter values. As a result, the tool posture that gradually changes over the entire removal volume can be set to the voxel attribution parameter.



(a) Setting of boundary tool posture



(b) Initialization of Voxel properties



(c) Diffusion of Voxel properties

Fig. 6. Setting the voxel properties for tool posture control.

In the numerical calculations, the time is discretized by the forward difference method, and the space is discretized by the central difference method. The physical quantity on a spatial lattice site at the $(n+1)-$th time step, f_{ijk}^{n+1}, can be calculated from the one at the $n-$th time step, f_{ijk}^{n}, by the following equation:

$$f_{ijk}^{n+1} = f_{ijk}^{n} + \Delta t D \left(\frac{f_{i+1jk}^{n} - 2f_{ijk}^{n} + f_{i-1jk}^{n}}{\Delta x^2} + \frac{f_{ij+1k}^{n} - 2f_{ijk}^{n} + f_{ij-1k}^{n}}{\Delta y^2} + \frac{f_{ijk+1}^{n} - 2f_{ijk}^{n} + f_{ijk-1}^{n}}{\Delta z^2} \right) \quad (5)$$

where Δt is the time step; D is the diffusion coefficient; and Δx, Δy, and Δz are the lattice spacings (sizes of the voxel that represents the removal volume). Those parameters are set as $\Delta t = 0.1$ s, $D = 40$, and $\Delta x = \Delta y = \Delta z = 2$ mm. The numerical calculation could be terminated in the middle of the diffusion process, but the calculation was continued until the physical quantity on the lattice sites reached a stable state.

For control of the rotational axis of the five-axis milling tool, the tool posture parameters θ and ϕ are converted to command values of the A and C axes (or B and C axes) of the machine tool.

Table 1. Cutting conditions for feed speed control.

Cutting Mode	Case 1: $x-z$ Scanning Line Case 2: Contour Line
Tool Shape	Ball Endmill
Tool Diameter [mm]	6
Work Materiel	Chemical Wood
Feed speed [mm/min]	$V_{Hi} = 800$, $V_{Lo} = 400$
Radial Depth of cut [mm]	2
Axial Depth of cut [mm]	2
Spindle Speed [rpm]	6000

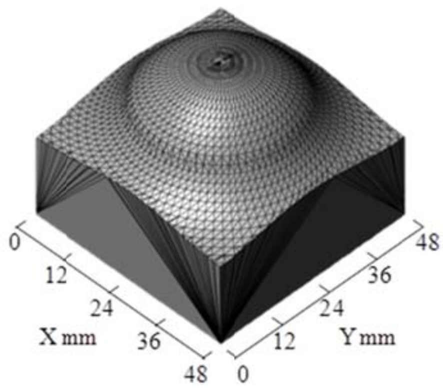


Fig. 7. 3D surface model for feed speed control.

4. Verification by Milling Experiments

The tool motion control algorithm proposed in the present chapter was implemented in the DCM system, and milling experiments were conducted to check the validity of the results. The machine tool used in the milling experiments was a five-axis vertical machining center (NMV1500DCG, DMG Mori Seiki). Commands for the tool path and tool motion control were given from a computer where the DCM system was implemented.

4.1. Tool Feed Speed Control

Table 1 lists the cutting conditions of the milling experiments. In the experiments, when the tool feed speed control function was used, the feed speed was determined by the diffusion equation with the upper limit of the feed speed set to $V_{Hi} = 800$ mm/min and the lower limit set to $V_{Lo} = 400$ mm/min. When the tool feed speed control function was not used, the feed speed was set to $V_{Lo} = 400$ mm/min. **Fig. 7** shows a 3D CAD model of the product shape. The smooth convex surface was machined in two modes: case 1: scanning-line cutting within the $x-z$ plane and case 2: contour-line cutting.

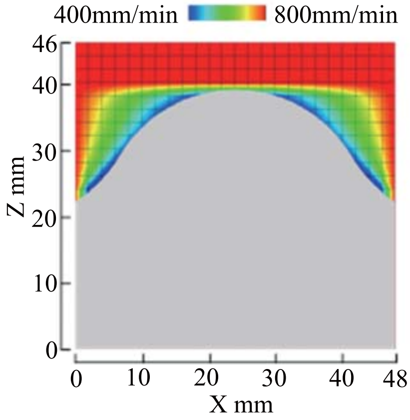


Fig. 8. Feed speed distribution for feed speed control ($x-z$ plane at $Y = 24$ mm).

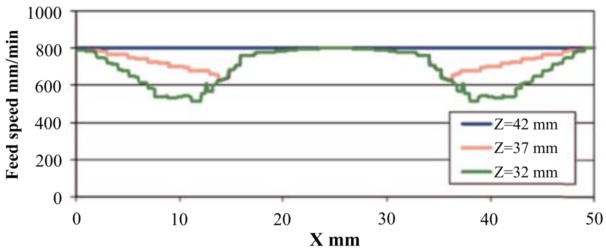


Fig. 9. Feed speed transition during milling operation (scanning-line mode along the X axis at $Y = 24$ mm).

Figure 8 shows the distribution of the tool feed speed in the x direction at $Y = 24$ mm. The figure shows that, when the cutting operation is started from the exterior of the material in the x direction, the tool feed speed is close to the upper limit when cutting the exterior area of the material and close to the lower limit when cutting the area near the product surface.

Figure 9 shows the change in the tool feed speed during the cutting operation at $Y = 24$ mm in the $x-z$ scanning-line mode. This figure also shows that the tool feed speed changed appropriately according to the z coordinate of the tool. The size of the voxel that represented the removal volume was 2 mm on a side; hence, the tool feed speed changed discretely, which then needed to be smoothed. The product shapes after the milling operations are shown in **Figs. 10(a)** and **10(b)**.

The cutting experiments demonstrated that the tool feed speed was appropriately controlled according to the tool feed direction and decreased as the tool approached the product surface. The same 3D CAD model of the product shape and the same voxel model of the removal volume were used for the tool path generation and the tool feed speed control in each of the two modes, and the tool feed control could be successfully controlled for both modes of the tool path generation.

(a) Scanning-line mode

(b) Contour-line mode

Fig. 10. Product shapes finished under feed speed control.

Table 2. Cutting conditions for tool posture control.

Cutting Mode	$x-z$ Scanning Line
Tool Shape	Ball Endmill
Tool Diameter [mm]	6
Work Materiel	Chemical Wood
Feed speed [mm/min]	4000
Radial Depth of cut [mm]	2
Axial Depth of cut [mm]	2
Spindle Speed [rpm]	9000

4.2. Tool Posture Control

The cutting conditions in the cutting experiments are listed in **Table 2**, and a 3D CAD model of the product shape is shown in **Fig. 11**. The experiments were conducted in the $x-z$ scanning-line mode. The z axis of the tool was set to be along the normal direction to the product surface, and the tool posture parameters θ and ϕ were limited up to $\pm 70°$ to prevent excessive tilting of the tool. **Fig. 12** shows the distribution of the tool posture parameter θ calculated with the diffusion equation at $Y = 10$, 20, 30, and 40 mm. Although the overhang shape varied depending on the cross sections, the tool posture gradually changed from the product surface to the exterior of the material. In this experiment, the collision between the tool and the workpiece was not considered. However, there are some studies on tool collision avoidance and tool

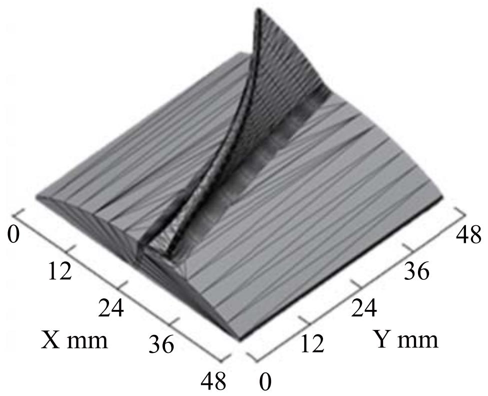


Fig. 11. 3D surface model for feed speed control.

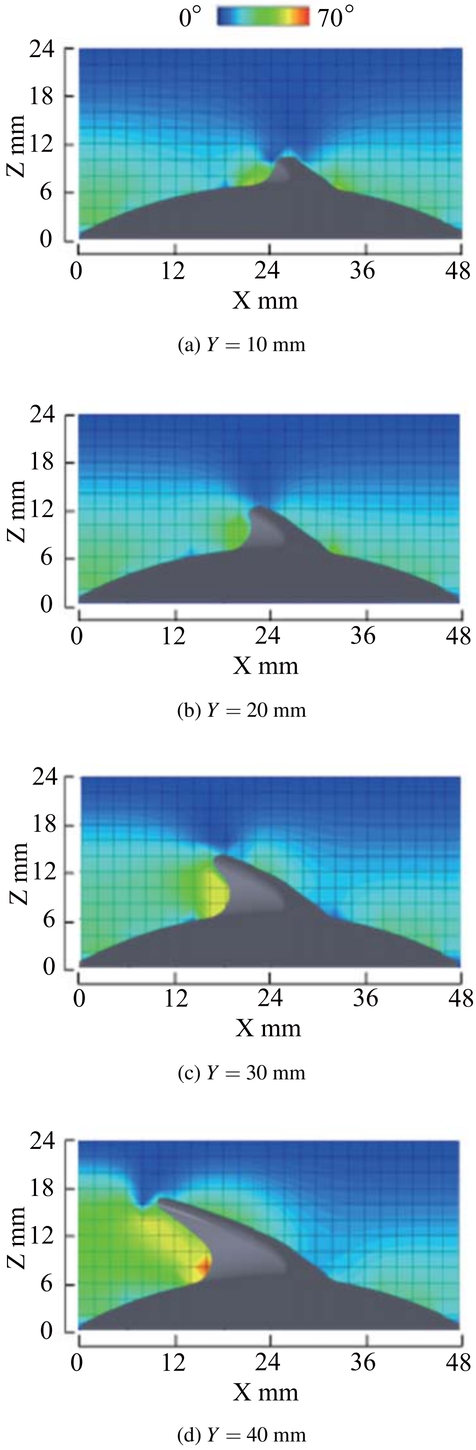


Fig. 12. Tool posture distribution for tool posture control.

posture determination [6–9], the tool posture can be determined carefully in advance with the voxel attribution parameters.

Figure 13 shows the change in the $B-$axis rotational angle specified during the cutting operations at each position of $Y = 10$, 20, 30, and 40 mm in the $x-z$ scanning-line mode experiments. One can see in the figure that the angle changed according to the z coordinate of the tool. The $B-$axis rotational angle changed discontinuously because the size of the voxel that represented the removal volume was 2 mm on a side; hence, the tool posture changed discretely. This needed to be smoothed.

The product shape after the milling operation is shown in **Fig. 14**. The cutting experiments demonstrated that the tool posture was appropriately controlled and that the z direction of the tool changed to the normal direction to the product surface as the tool approached the product surface.

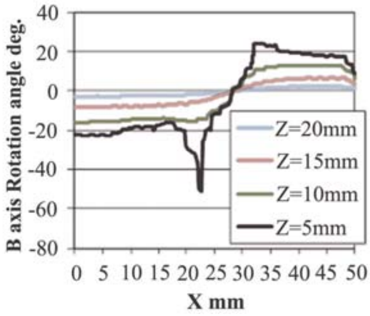
5. Conclusions

In this study, a tool motion control function was added to the DCM system for creating tool paths based on a 3D CAD model of the product shape to improve the flexibility and autonomy of the machine tools and confirmed the validity of the system using cutting experiments with a five-axis vertical machining center.

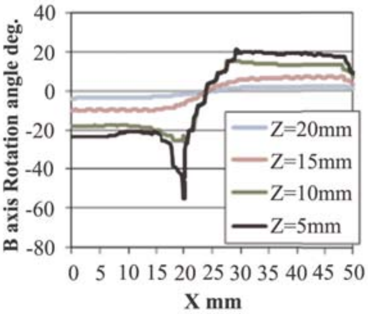
1. A new tool motion control method was proposed and realized. In this method, the removal volume was presented with a voxel model, and voxel information such as tool feed speed and tool posture that was configured as attribution parameters of each voxel was referred to during cutting operation to control the tool motion.

2. The situation in which the tool feed speed and tool posture gradually changed as the tool motion during the cutting operation was recognized as a diffusion phenomenon. The voxel attribution parameters over the entire removal volume were determined with a diffusion equation to determine the tool feed speed and tool posture over the entire removal volume based on the locally specified speed and posture.

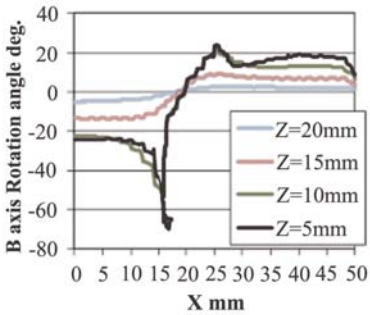
3. Cutting experiments were conducted with the proposed tool motion control algorithm implemented in the DCM system, and it was verified that the tool feed speed and tool posture could be appropriately controlled according to the position and feed direction of the tool during cutting operation.



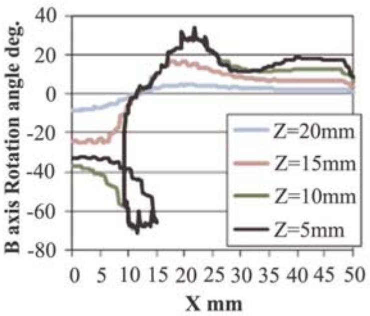
(a) $Y = 10$ mm



(b) $Y = 20$ mm



(c) $Y = 30$ mm



(d) $Y = 40$ mm

Fig. 13. Tool posture transition during machining operation.

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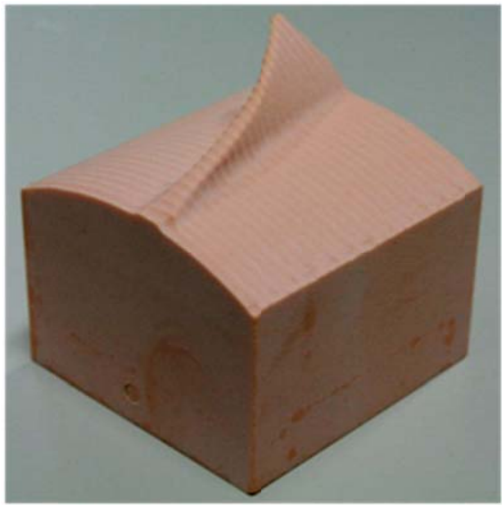

Fig. 14. Product shape finished under tool posture control.

References:

[1] T. Moriwaki, "Intelligent machine Tool," J. of JSME, Vol.96, No.901, pp. 1010-1014, 1993. (in Japanese)

[2] K. Shirase, T. Kondo, M. Okamoto, H. Wakamatsu, and E. Arai, "Development of Virtual Copy Milling System to Realize NC Programless Machining (1st Report)," Trans. of JSME(C), Vol.66, No.644, pp. 1368-1373, 2000. (in Japanese)

[3] K. Nakamoto, K. Shirase, H. Wakamatsu, A. Tsumaya, and E. Arai, "Development of Virtual Copy Milling System to Realize NC Programless Machining (2nd Report)," Trans. of JSME(C), Vol.67, No.663, pp. 3656-3661, 2001. (in Japanese)

[4] K. Nakamoto, K. Shirase, H. Wakamatsu, A. Tsumaya, and E. Arai, "Development of Virtual Copy Milling System to Realize NC Programless Machining (3rd Report)," Trans. of JSME(C), Vol.69, No.677, pp. 270-277, 2003. (in Japanese)

[5] K. Shirase, T. Shimada, and K. Nakamoto, "Prototyping of Autonomous CNC Machine Tool Based on Digital Copy Milling Concept," Proc. of the 41st CIRP Conf. on Manufacturing Systems, pp. 391-394, 2008.

[6] K. Morishige, K Kase, and Y. Takeuchi, "Tool Path Generation Using C-Space for 5-Axis Control Machining," J. of JSPE, Vol.62, No.12, pp. 1783-1787, 1996. (in Japanese)

[7] H. Wkayama and K. Morishige, "Optimum Tool Path Generation for 5-Axis Control Machining Considering Tool Attitude Change," J. of JSPE, Vol.71, No.5, pp. 639-643, 2005. (in Japanese)

[8] J. Kaneko and K. Horio, "Fast Determination Method of Tool Posture for 5-Axis Control Machining Using Graphics Hardware : Estimation of machinable posture on 2D C-Space based on intersection between offset surface and lines of view," J. of JSPE, Vol.72, No.8, pp. 1012-1017, 2006. (in Japanese)

[9] M. Yamada, F. Tanaka, T. Kondo, and T. Kishinami, "Sculpture Surface Machining by Automatically Indexing Tilted Tool Axis on 5-axis Machine Tools (3rd report)," J. of JSPE, Vol.73, No.5, pp. 563-567, 2007. (in Japanese)

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- T. Shimada, K. Nakamoto, and K. Shirase, "Machining Strategy to Adapt Cutting Conditions under Digital Copy Milling Concept," J. of Advanced Mechanical Design, Systems, and Manufacturing, Special Issue on Advanced Manufacturing Technology, Vol.4, No.5, pp. 924-935, 2010.
- K. Shirase and K. Nakamoto, "Simulation Technologies for the Development of an Autonomous and Intelligent Machine Tool," Int. J. of Automation Technology, Vol.7, No.1, pp. 6-15, 2013.

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