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Paper:

Surface Roughness Control Based on Digital Copy Milling Concept to Achieve Autonomous Milling Operation

Toshihiko Hirooka[*1], **Tomokazu Kobayashi**[*2], **Atsushi Hakotani**[*3],
Ryuta Sato[*1], **and Keiichi Shirase**[*1]

[*1]Graduate School of Engineering, Kobe University
1-1 Rokko-dai, Nada, Kobe 657-8501, Japan
E-mail: shirase@mech.kobe-u.ac.jp
[*2]Nissan Motor Co., Ltd.
1-1 Morinosato-aoyama, Atsugi, Kanagawa 243-0123, Japan
[*3]Kawasaki Heavy Industries Ltd.
1-1 Kawasaki-cho, Akashi, Hyogo 673-8666, Japan

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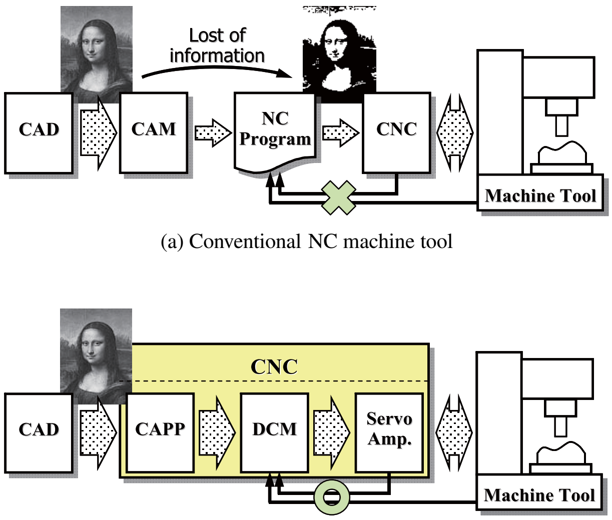
An autonomous and intelligent machine tool that performs machining operations by referring to CAD product data was developed in our previous study to solve fundamental issues with the conventional command method, which uses NC programs. A system, Digital Copy Milling (DCM), digitizing the principle of copy milling, was developed to generate tool paths during milling operations for dynamic tool motion control. In the DCM, the cutting tool is controlled dynamically to follow the surface of a CAD model corresponding to product shape, eliminating the need for the preparation of NC programs. Active tool motion controls were also realized to enhance the function of DCM. In this study, surface roughness control of the finished surface is realized as an additional enhanced function of DCM to achieve autonomous milling operations. This function allows the DCM to select cutting conditions and generates tool paths dynamically to produce the desired surface roughness: from rough, through semi-finished, to finished. The verification experiment is successfully carried out.



(a) Conventional NC machine tool

(b) Autonomous and intelligent NC machine tool

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

Keywords: autonomous and intelligent machine tool, Digital Copy Milling (DCM), tool motion control, surface roughness control, finishing

1. Introduction

NC machine tools have been widely used to achieve unmanned machining with high quality and productivity. However, NC programs, which are needed for unmanned operation of NC machine tools, require a huge amount of time and effort in terms of CAM operation. Additionally, making trouble-free NC programs for advanced machining operations utilizing a multi-axis or multi-tasking machine tool requires much more time and effort. Therefore, an autonomous and intelligent machine tool which can operate easily and safely is needed to solve these problems. Additionally, in order to solve fundamental issues with the conventional command method using NC programs, a new concept is needed to achieve an autonomous and intelligent machine tool.

Figure 1 shows our proposed concept of an autonomous and intelligent NC machine tool compared to a conventional NC machine tool.

A conventional NC machine tool is not able to change instructions or NC commands dynamically during a machining operation. On the other hand, an autonomous and intelligent NC machine tool can perform machining operations by referring to 3D CAD data of the product only. It has a real-time tool path generation function, and it can change cutting conditions dynamically for flexible machining process control and cutting trouble avoidance. It can also make a process plan by referring to 3D CAD data

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of the product. Furthermore, by utilizing the results of the machined product or cutting conditions for the next machining project, much more autonomous and intelligent machining operations are possible.

In our previous studies, the new concept, Digital Copy Milling (DCM), which digitizes the principle of copy milling, was proposed to realize real-time tool path generation for a conventional three-axis NC machine tool. In the experimental milling of sculptured surfaces, not only the feed rate but also radial and axial depths of cut could be modified during machining operations [1]. Additionally, autonomous milling process control using the DCM was realized. In the experimental milling, cutting conditions, even radial and axial depths of cut, could be adapted to keep the cutting force stable during a milling operation [2]. Furthermore, the tool breakage was successfully avoided using a prototype of the autonomous and intelligent NC machine tool controlled by the DCM concept. In the experimental tool crash condition, the cutting tool was retracted safely to avoid tool breakage [3].

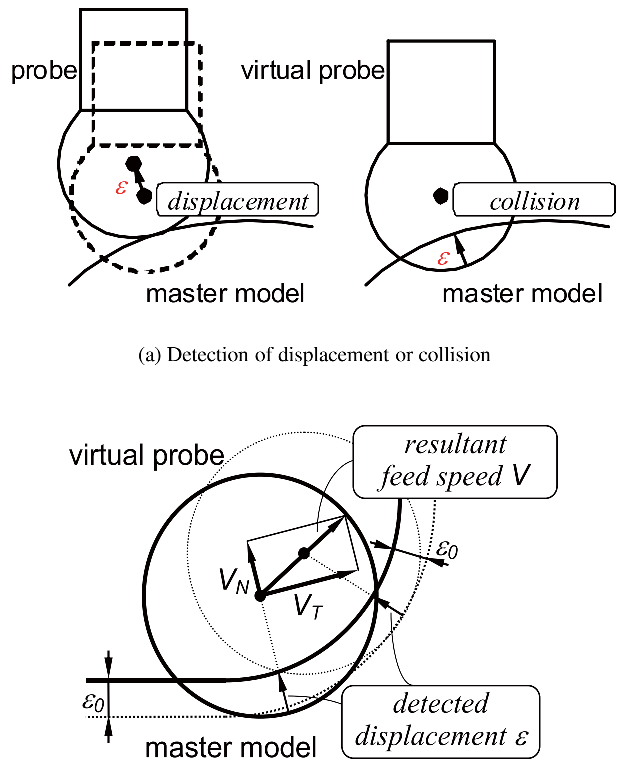
2. Principle of Digital Copy Milling

About two decades ago, several tool path generation methods for free form surface were proposed. Some of them generated curves to drive the milling tool, curves which intersected the surface with equally spaced parallel planes [4–5]. Alternative methods provide an offset surface to the surface model at a distance equal to the radius of the ball end mill [6–7]. In the reference [7], Bezier and NURBs surface approximations were introduced. These methods aimed to generate high quality and precision tool paths, which can become huge and complicated in accordance with the precision and complexity of the products being machined.

However, these methods did not focus on achieving autonomous and flexible machining operations to change cutting parameters for machining process control and cutting trouble avoidance.

The DCM generates tool paths in real-time to achieve autonomous and flexible machining operations. This is the biggest advantage and difference between the DCM and the command method using NC programs. In order to realize real-time tool path generation, the control principle of copy milling is applied to the DCM.

In conventional copy milling, the tool motion is controlled to correspond to the motion of the tracing probe. The tracing probe is handled manually by a machining operator to follow the master model, which has the same shape as the product. In the DCM, a 3D CAD model of the product is used instead of the master model for conventional copy milling. The maximum collision between geometric 3D models of the virtual tracing probe and the virtual master model, which corresponds to the displacement detected by the tracing probe in conventional copy milling, is detected as shown in **Fig. 2(a)**. In **Fig. 2(b)**, the displacement or the collision ε is detected and ε_0 is the target displacement of displacement ε. Also, V_N and V_T are normal and tangential feed speed to the model surface, and both of them are determined by displacement ε. Resultant feed speed V of tool motion is calculated from V_N and V_T [1].



(a) Detection of displacement or collision

(b) Feed speed control

Fig. 2. Feed speed control in Digital Copy Milling.

In order to simplify the tool motion, the scanning line mode for both unilateral and bilateral (or zigzag) paths and the contour line mode are prepared as the basic tool path pattern in the DCM. In the DCM, a machined shape, a material shape, tool properties and cutting parameters are required as the input information for the milling operation. Tool paths or Cutter Location (CL) data are generated in real time, and the milling tool is controlled to follow the motion of the virtual probe as shown in **Fig. 3**.

The geometric 3D model of the virtual tracing probe detects a collision with the virtual master model, and the cutting tool is controlled to follow the virtual master model, which has the product shape. The DCM can generate tool paths for the entire operation without the need for creating NC programs beforehand.

3. Voxel Representation of Removal Volume

In conventional NC machine tools, tool motion is instructed by G-code which corresponds to G00, G01, G02, G03 etc. Tool motion is controlled by point for positioning and by line for contouring. In the DCM, tool motion is controlled by the surface. In this study, voxel representation of removal volume is introduced to enhance

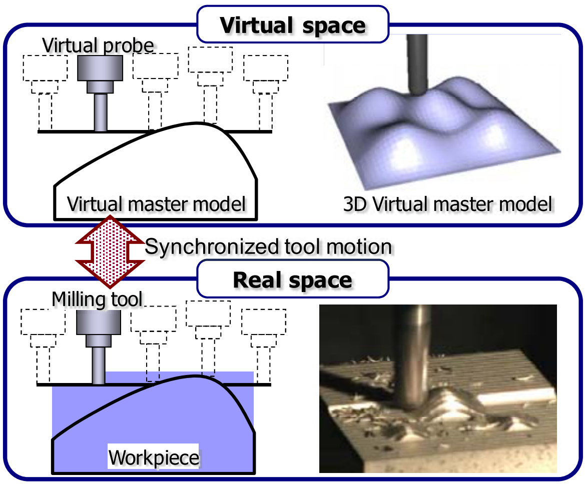


Fig. 3. Milling operation performed by DCM.

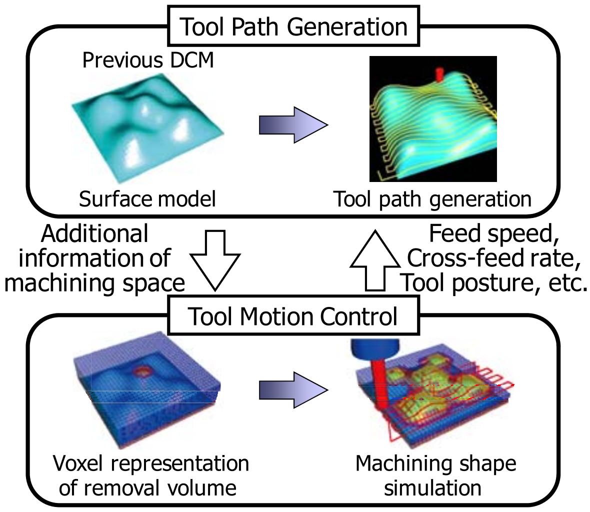
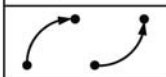
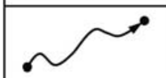
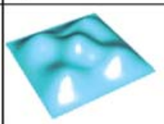
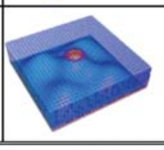


Fig. 4. Voxel representation and utilization of voxel property for tool motion control.

Table 1. Tool motion control in conventional NC program and DCM.

Conventional tool motion control	Point		Rapid positioning G00
	Line		Linear interpolation G01
			Circular interpolation G02, G03
			Spline interpolation NURBUS interpolation
Tool motion control in DCM	Surface		Digital Copy Milling (DCM)
	Volume		Voxel representation of removal volume and DCM

the function of the DCM. The volume information corresponding to the voxel property is utilized for active tool motion control. It means that the DCM is intended to utilize higher-level information than conventional G-code commands for tool motion control, as shown in **Table 1**.

In this study, the finished surface is represented by a 3D surface model to generate tool paths precisely as same as those generated by previous DCM. In addition, the shape of the raw material is represented by voxels to ascertain the tool situations in the milling operation. The tool situations, such as in cutting or air-cutting motions, in engaging or disengaging motions, relative tool position to the finished surface, etc., can be detected by means of machining shape simulation. Tool motion can be controlled properly according to the tool situation detected. Furthermore, it is possible to set several codes or values as voxel properties to utilize for tool motion control. Some codes can be used to change machining strategies, and some values can be used to adapt to cutting conditions. By utilizing voxel properties, tool motion control can be performed independently of the tool path generation, as shown in **Fig. 4**.

During the milling operation, the DCM generates the tool paths precisely using a 3D surface model of the finished surface. On the other hand, the active tool motion control can be achieved by referring to the voxel properties. In some cases, the voxel properties can be set dynamically according to the results of machining shape simulation. In other cases, the voxel properties can be set statically according to the machining strategy.

In our previous studies, tool feed speed control was realized by referring to information on the distance from the finished surface [8], and tool posture control was realized by referring to information on tool inclination angles [9].

4. Surface Roughness Control Function

In our previous studies, surface quality was not considered. In this paper, surface roughness control for finish cutting is considered to achieve much more autonomous machining operations. Good surface roughness and high machining productivity are especially competitive objectives. Therefore, dynamic changes in cutting conditions and machining strategy will be effective to achieve both good surface roughness and high machining productivity. For this purpose, voxel properties corresponding to the surface roughness are utilized to select suitable cutting conditions and machining strategies during machining operations. In this study, three levels of surface quality, *Ra* 12.5, *Ra* 3.2, and *Ra* 1.6, are considered for surface roughness control.

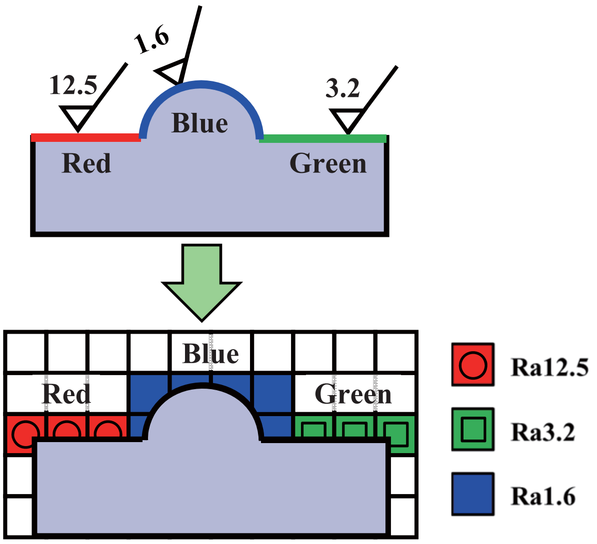


Fig. 5. Surface roughness parameters set into voxel properties.

4.1. Surface Roughness Parameter in Voxel Property

A Virtual Reality Modeling Language (VRML) format is utilized to import both the machined shape and the surface roughness parameters into the DCM. A VRML format consists of coordinates of triangle mesh vertexes and the surface colors and surface ID of a 3D surface model. The surface roughness is therefore represented by different surface color, and the surface roughness parameter in the voxel property can be set according to the surface color noted in VRML format. The voxel properties of voxels on the 3D surface model corresponding to the finished surface are set, as shown in **Fig. 5**. In this study, red corresponds to *Ra* 12.5, green corresponds to *Ra* 3.2, and blue corresponds to *Ra* 1.6.

Furthermore, in order to improve surface quality in finish cutting, the following four functions are realized.

4.2. Tool Inclination Angle

In milling operations using ball end mills, no tool inclination angle generates low surface quality because of the zero cutting speed at the tool tip. In this study, tool inclination angles are set properly to avoid zero cutting speed at the tool tip. It was reported that the surface quality is improved by milling with greater than ± 10 degrees of lead angle or more than 10 degrees of tilt angle [10]. Therefore, in rough- cutting, a zero lead angle and zero tilt angle are set. In semi-finish- cutting and finish- cutting, -20 degrees of lead angles and a zero tilt angle are set to generate good surface quality.

In order to simplify the tool motion control, tool interference is not considered in this study. In practical use, suitable tool inclination angles have to be determined to avoid tool interference. Once the suitable tool inclination angles have been determined, tool posture control can be realized to avoid tool interference [9].

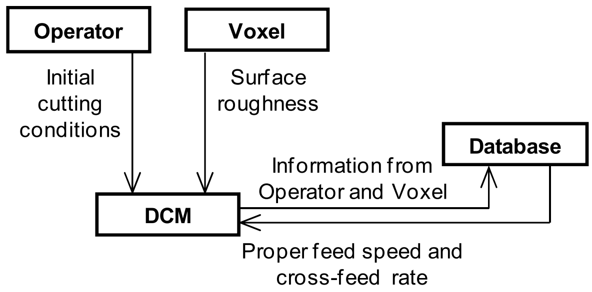


Fig. 6. Selection of cutting conditions for finish-cutting.

4.3. Selection of Cutting Conditions in Finish Cutting

To satisfy the surface quality instructed by surface roughness *Ra*, feed speed and cross-feed rate for finish cutting are selected properly according to the surface roughness.

Figure 6 shows the flow of selecting cutting conditions for finish cutting. First, the DCM receives initial cutting conditions and the workpiece material from the operator and surface roughness parameters from voxel properties. Then the database replies with proper feed speed and cross-feed rate based on initial cutting conditions and surface roughness parameters. In this study, tool feed speed and cross-feed rate for finish cutting are selected from the results of preliminary experiments, which show the relation between cutting conditions and surface roughness. Cutting conditions are selected by referring to the theoretical surface roughness and the database of cutting conditions.

The theoretical surface roughness is estimated by following formulas shown as Eqs. (1) and (2). However, the theoretical surface roughness shows the best surface roughness finished with no disturbances, such as vibration, tool deflection, tool wear, and so on. Therefore, some correction factor is needed to predict practical surface roughness.

$$F = \sqrt{\frac{8 \times R \times R_Z}{1000}} \times S \times Z \quad \text{. . . . . (1)}$$

$$P = \sqrt{\frac{8 \times R \times R_Z}{1000}} \quad \text{. . . . . (2)}$$

F : Tool feed speed,

P : Cross-feed,

R : Tool radius,

R_Z : Maximum height roughness

S : Spindle speed,

Z : Number of flutes

The database of cutting conditions is referred to find the correction factor for the prediction of the practical surface roughness. In this study, finish cutting experiments are performed with several different tool feed speeds and cross-feed rates, and the surface roughness is measured to make the initial database. The surface roughness measured in both the feed and cross-feed directions are summarized in **Fig. 7**. The most suitable cutting conditions of feed speed and cross-feed rate for finish cutting can be selected according to those results for each surface roughness *Ra* conveyed.

4.4. Process Plan of Milling Operation

In order to achieve good surface quality, the three steps, of rough- cutting, semi-finish- cutting and finish- cutting operations, are performed sequentially. First, rough- cutting operation is performed, as shown in **Fig. 8(a)**. Then, semi-finish- cutting is performed for the area of surface roughness *Ra* 12.5. In this step, 0.05 mm stock allowance is left for the area of surface roughness *Ra* 12.5, and 0.15 mm stock allowance is left for the areas of surface roughness *Ra* 3.2 and 1.6, as shown in **Fig. 8(b)**.

Then, finish- cutting for the area of surface roughness *Ra* 12.5 and semi-finish- cutting for the areas of surface roughness *Ra* 3.2 and 1.6 are performed. In this step, 0.05 mm stock allowance is left for finish- cutting for the areas of the surfaces roughness *Ra* 3.2 and 1.6 as shown in **Fig. 8(c)**.

Finally, finish- cutting for the area with surface roughness *Ra* 3.2 (see **Fig. 8(d)**), and finish- cutting for the area with surface roughness *Ra* 1.6 (see **Fig. 8(e)**) are performed, separately.

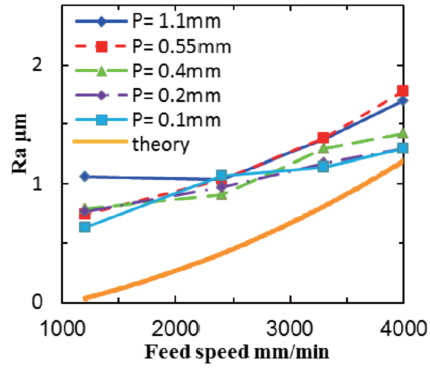
4.5. Partitioning of Cutting Areas

To reduce machining time, cutting areas are sectionalized automatically according to the surface roughness *Ra* conveyed. In rough- cutting, semi-finish- cutting, and finish- cutting for the area of surface roughness *Ra* 12.5, the area covering the entire machined surface is recognized as the cutting area. On the other hand, in finish- cutting for the areas of surface roughness *Ra* 3.2 and *Ra* 1.6, the area consisting of the successive voxels which have the same property of surface roughness *Ra* and surface ID are recognized as the cutting area.

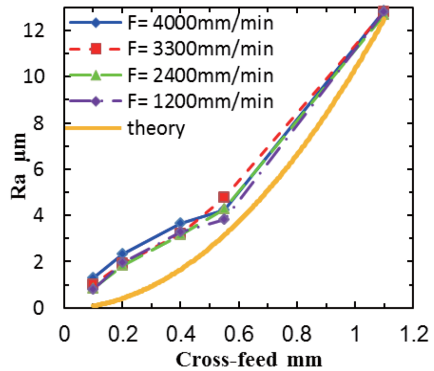
Figrue 9 shows an example of partitioned cutting areas with surface roughness *Ra* 3.2 and *Ra* 1.6, which are recognized and identified automatically by referring to the voxel properties. Finish cutting is performed according to the partitioned areas, one by one.

5. Cutting Experiments

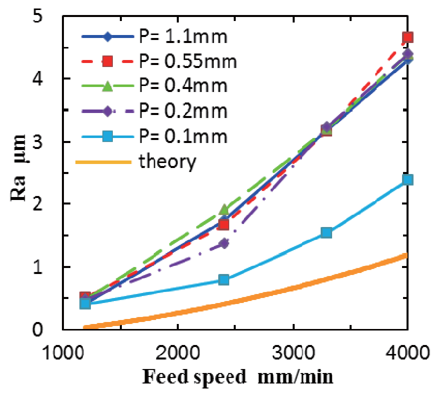
In order to verify the effectiveness of the proposed concept, which aims to enhance the function of the DCM, cutting experiments were performed using a vertical 5-axis machining center NMV1500DCG (MORI SEIKI CO., LTD.). The cutting conditions of these experiments are summarized in **Table 2**. Cutting conditions for finish-cutting, which are determined automatically according to the voxel properties or the surface roughness *Ra*, are summarized in **Table 3**. In this table, cutting conditions for



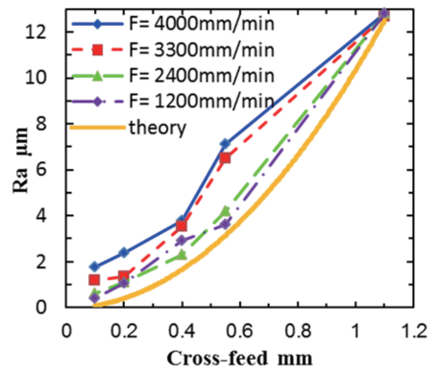
(a) Surface roughness in feed direction (material: FC250)



(b) Surface roughness in cross feed direction (material: FC250)

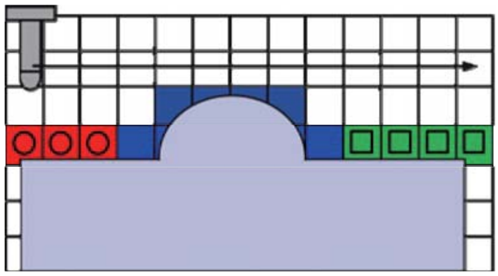


(c) Surface roughness in feed direction (material: A2017P)

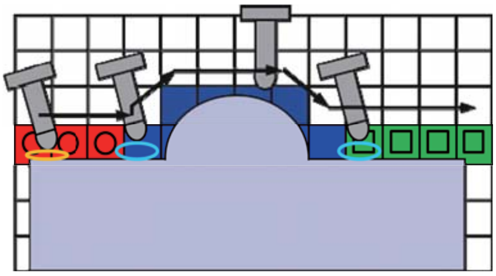


(d) Surface roughness in cross feed direction (material: A2017P)

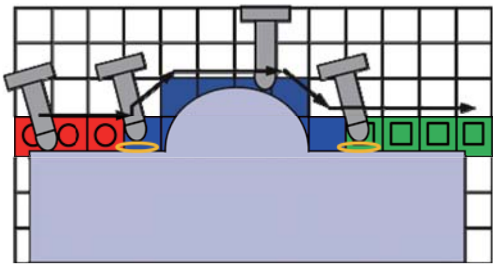
Fig. 7. Surface roughness achieved in preliminary experiment.



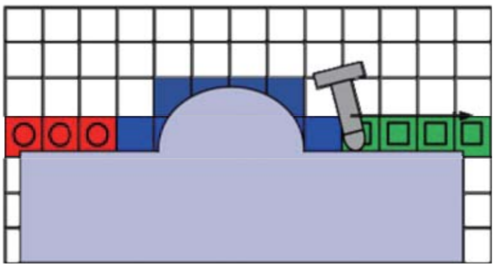
(a) Rough- cutting



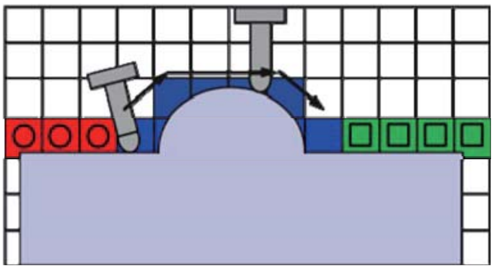
(b) Semi-finish- cutting for the area of *Ra* 12.5



(c) Finish- cutting for the area of *Ra* 12.5



(d) Finish- cutting for the area of *Ra* 3.2



(e) Finish- cutting for the area of *Ra* 1.6

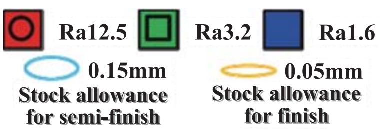


Fig. 8. Cutting operations from rough- cutting, semi-finish- cutting, and finish- cutting.

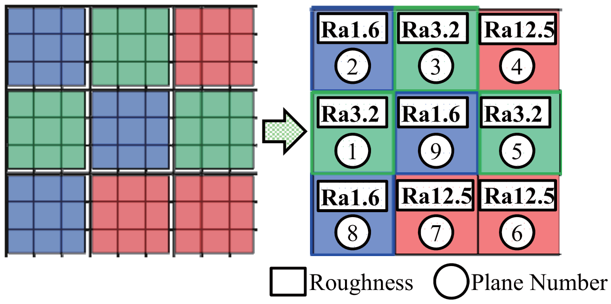


Fig. 9. Partitioned cutting areas and area number.

Table 2. Cutting conditions for rough-cutting.

Tool path pattern	Zigzag
Work material	FC250 and A2017P
Cutting tool	Ball end mill (2 flutes)
Tool diameter	6 mm
Radial depth of cut	2 mm
Axial depth of cut	0.5 mm
Rapid feed speed	1500 mm/min
Spindle speed	6000 min^{-1}
Voxel size	2 mm

Table 3. Cutting conditions for finish-cutting.

		Feed speed	Cross-feed rate
FC250	*Ra* 12.5	4000 mm/min	1.0 mm
	Ra 3.2	4000 mm/min	0.2 mm
	Ra 1.6	3000 mm/min	0.1 mm
A2017P	*Ra* 12.5	4000 mm/min	1.0 mm
	Ra 3.2	3000 mm/min	0.3 mm
	Ra 1.6	2000 mm/min	0.2 mm

both work materials, FC250 and A2017P, are summarized. The DCM generated tool paths autonomously during milling operations from rough- cutting, through semi-finish- cutting, to finish- cutting.

A 3D CAD model using experimental verification is shown in **Fig. 10**. The finished shape and the surface roughness *Ra* represented in a VRML format were delivered to the DCM for this cutting experiment. The CAD model, which consists of nine square planes, is very simple to check the performance of surface roughness control. However, it is obviously that the DCM has the ability to machine the practical shape as demonstrated in our previous study [11]. Therefore, the surface roughness control is applicable to the practical shape immediately.

Figure 11 is a view of the cutting experiment involving work material FC250. In this experiment, the workpiece was tilted to avoid zero speed cutting at the tool tip. Cutting operations from rough- cutting to semi-finish- cutting to finish- cutting were performed sequentially ac-

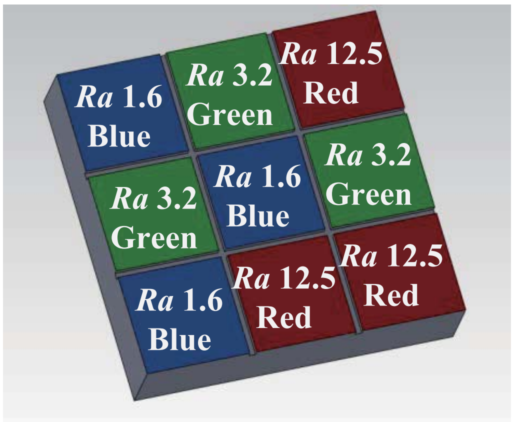


Fig. 10. 3D CAD model using experimental verification.

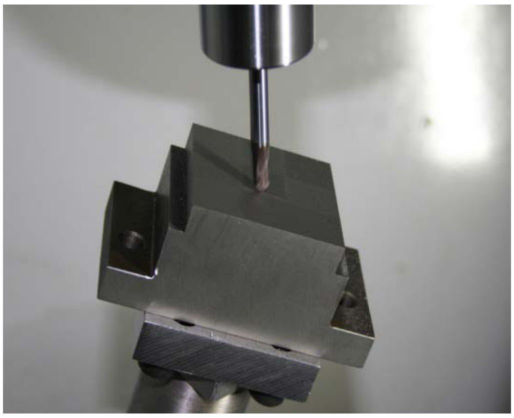


Fig. 11. Cutting experiment (material: FC250).

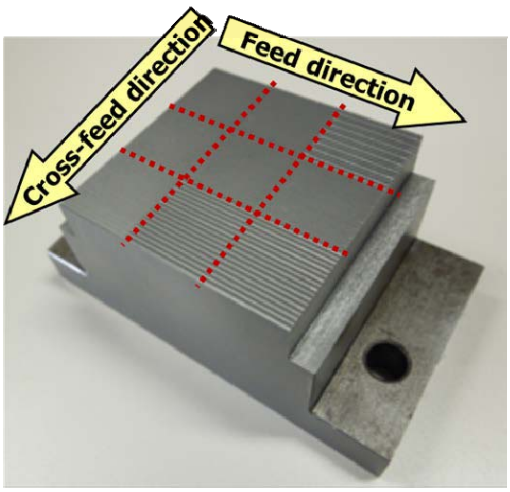


Fig. 12. Finished surface (material: FC250).

Ra_f 1.18 µm Ra_p 1.44 µm	Ra_f 1.67 µm Ra_p 2.74 µm	Ra_f 2.17 µm Ra_p 10.6 µm
Ra_f 1.97 µm Ra_p 2.24 µm	Ra_f 1.10 µm Ra_p 1.36 µm	Ra_f 1.50 µm Ra_p 2.84 µm
Ra_f 1.26 µm Ra_p 1.48 µm	Ra_f 2.52 µm Ra_p 10.2 µm	Ra_f 2.59 µm Ra_p 8.72 µm

Ra 12.5 Ra 3.2 Ra 1.6

(a) Work material FC250

Ra_f 1.22 µm Ra_p 0.72 µm	Ra_f 2.84 µm Ra_p 2.81 µm	Ra_f 4.68 µm Ra_p 10.2 µm
Ra_f 2.98 µm Ra_p 2.32 µm	Ra_f 1.25 µm Ra_p 1.01 µm	Ra_f 2.68 µm Ra_p 2.56 µm
Ra_f 1.03 µm Ra_p 1.03 µm	Ra_f 3.81 µm Ra_p 9.52 µm	Ra_f 4.46 µm Ra_p 9.60 µm

Ra 12.5 Ra 3.2 Ra 1.6

(b) Work material A2017P

Fig. 13. Results of measured surface roughness.

cording to the strategy mentioned above. Also, the cutting areas were clearly demarcated, and the stock allowance for semi-finish- cutting and finish- cutting were reserved properly in each step.

Surface roughness control was performed successfully to select the feed speed and cross-feed rate for the two work materials, FC250 and A2017P.

Figure 12 shows the finished surface of the work material FC250 generated by this cutting experiment. It clearly shows that the different surface qualities were generated.

Finished surface roughness was measured at each cutting area along both the tool-feed and cross-feed directions. All measurements of surface roughness *Ra* for each cutting area are summarized in **Fig. 13**. The results for the work materials FC250 and A2017P are shown in **Figs. 13(a)** and **(b)**, respectively. Ra_f and Ra_c correspond to the measured surface roughness *Ra* in the feed and cross-feed directions, respectively. All measured surface roughness *Ra* was less than the surface roughness *Ra* conveyed. These results show that the surface roughness control can be performed successfully under the proposed concept.

6. Conclusion

Voxel representation of removal volume has been presented to enhance the functions of the Digital Copy Milling (DCM) system, which digitizes the principle of copy milling. In this study, the surface roughness control of finished surfaces was successfully realized.

(1) A VRML format is utilized to convey the surface roughness *Ra* by surface color of a 3D surface model to the DCM.

(2) The DCM can perform rough- cutting, semi-finish-cutting, and then finish- cutting automatically by selecting suitable cutting conditions according to the surface roughness *Ra* conveyed.

(3) The experimental verification was performed successfully and all measured surface roughness *Ra* was less than the surface roughness *Ra* conveyed.

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Name:
Toshihiko Hirooka

Affiliation:
Master Course Student, Graduate School of Engineering, Kobe University

Address:
1-1 Rokko-dai, Nada, Kobe 657-8501, Japan

Brief Biographical History:
2012 Graduated from Faculty of Engineering, Kobe University
2012- Master Course Student, Graduate School of Engineering, Kobe University

Membership in Academic Societies:
• The Japan Society for Precision Engineering (JSPE)

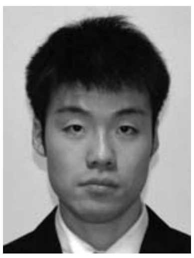
Name:
Tomokazu Kobayashi

Affiliation:
Nissan Motor Co., Ltd.

Address:
1-1 Morinosato-aoyama, Atsugi, Kanagawa 243-0123, Japan

Brief Biographical History:
2011 Graduated from Faculty of Engineering, Kobe University
2013 Graduated from Graduate School of Engineering, Kobe University
2013- Joined Nissan Motor Co., Ltd.

Membership in Academic Societies:
• The Japan Society for Mechanical Engineer (JSME)



Name:
Atsushi Hakotani

Affiliation:
Kawasaki Heavy Industries, Ltd.

Address:
1-1 Kawasaki-cho, Akashi, Hyogo 673-8666, Japan

Brief Biographical History:
2010 Graduated from Faculty of Engineering, Kobe University
2012 Graduated from Graduate school of engineering , Kobe University
2012- Joined Kawasaki Heavy Industries, Ltd.

Membership in Academic Societies:
• The Japan Society of Mechanical of Engineers (JSME)

Name:
Ryuta Sato

Affiliation:
Associate Professor, Department of Mechanical Engineering, Graduate School of Engineering, Kobe University

Address:
1-1 Rokko-dai, Nada, Kobe 657-8501, Japan

Brief Biographical History:
2004- Research Associate, Tokyo University of Agriculture and Technology
2008- Researcher, Mitsubishi Electric Corporation
2010- Assistant Professor, Kobe University
2013- Associate Professor, Kobe University

Main Works:
- "Influence of Motion Error of Feed Drive Systems on Machined Surface," J. of Advanced Mechanical Design, Systems, and Manufacturing, Vol.6, No.6, pp. 762-767, 2012.
- "Generation Mechanism of Quadrant Glitches and Its Compensation of Feed Drive Systems for NC Machine Tools," Int. J. of Automation Technology, Vol.6, No.2, pp. 154-162, 2012.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society for Precision Engineering (JSPE)
- The Society of Instrument and Control Engineers (SICE)

Name:
Keiichi Shirase

Affiliation:
Professor, Department of Mechanical Engineering, Graduate School of Engineering, Kobe University

Address:
1-1 Rokko-dai, Nada, Kobe 657-8501, Japan

Brief Biographical History:
1984- Research Associate, Kanazawa University
1995- Associate Professor, Kanazawa University
1996- Associate Professor, Osaka University
2003- Professor, Kobe University

Main Works:
- K. Shirase, K. Nakamoto, E. Arai, and T. Moriwaki, "Real-Time Five-Axis Control Based on Digital Copy Milling Concept to Achieve Autonomous Milling," Int. J. of Automation Technology, Vol.2, No.6, pp. 418-424, 2008.
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Membership in Academic Societies:
- The American Society of Mechanical Engineers (ASME)
- The Society of Manufacturing Engineers (SME)
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society for Precision Engineering (JSPE)