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(Citation)
International Journal of Automation Technology,14(6):1036-1044

(Issue Date)
2020-11-05

(Resource Type)
journal article

(Version)
Version of Record

https://doi.org/10.20965/ijat.2020.p1036

Paper:

Automated Tool Path Generation for Roughing Using Flat Drill

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[Received April 22, 2020; accepted September 4, 2020]

A method to calculate tool path uniquely for roughing using a flat drill is proposed. A flat drill is a drill with a flat tip. Unlike a square end mill, it cannot feed a tool laterally, but it is suitable for machining to feed a tool longitudinally. The advantage offered by the flat drill is expected to reduce machining troubles, such as tool breakages and chatter vibration, owing to the axial sturdiness of the tool. Furthermore, it can be used to machine lapped holes that cannot be machined with a normal drill owing to its flat tip. Hence, roughing using a flat drill by drilling multiple holes at constant intervals is proposed herein. Furthermore, in this method, a tool path for semi-finishing is generated only on the remaining region. A cutting experiment is conducted to validate the effectiveness of the proposed method. The result of the cutting experiment confirmed the effectiveness of the proposed method based on the machining time and the productivity of machining multiple products simultaneously.

Keywords: CAM, flat drill, roughing, end milling

1. Introduction

Flexible manufacturing or customized manufacturing is required for the limited production of diversified products. The time and cost for preparation, such as NC program generation, significantly affects the production efficiency. Some previous studies have attempted to reduce the time required to generate an NC program, in which digital copy milling is realized without an NC program [1–4]. Meanwhile, computer-aided process planning (CAPP) systems were used in other studies to automatically generate an NC program. To automatically generate an NC program, the machining shape must be recognized and the machining conditions determined. A computer is not effective in recognizing the machining shape as it cannot understand the geometric features of a complicated product shape. Therefore, the machining feature on the product shape must be recognized. Two main methods are used for machining feature recognition: recognizing a target shape [5–9] and recognizing a removal volume [10–19]. To determine the machining conditions, the knowledge of experienced operators is necessitated because the difference in the feed speed or the axial and radial depth of cut significantly affects the productivity. Subsequently, it must be determined automatically. Some previous studies have attempted to automatically determine the machining conditions based on the geometric features of the product shape [20–22]. Other studies realized this by reusing machining case data [23, 24]. Although NC programs have been generated automatically in some studies, this method is difficult to apply to the machining site because the product shape is typically extremely complicated for recognizing the machining feature, and the combination of workpiece material, machine tool, and cutting tool is not always constant.

This study aims to realize the automated generation of an NC program. Hence, a method is proposed to calculate the tool path for roughing using a flat drill to suppress machining troubles and improve machining efficiency during roughing. A flat drill is a drill with a flat tip. Unlike a square end mill, it cannot feed a tool laterally, but it is suitable for machining to feed a tool longitudinally. Based on the advantages of the flat drill, machining troubles such as tool breakages and chatter vibration are expected to be reduced because of the axial sturdiness of the tool. Furthermore, it can be used to machine lapped holes that cannot be machined using a normal drill owing to its flat tip. Hence, this study proposes roughing using a flat drill by drilling multiple holes at constant intervals. Furthermore, in this method, a tool path is generated for semi-finishing only on the remaining region. In this study, a cutting experiment was conducted to validate the effectiveness of the proposed method.

2. Tool Path Generation for Roughing Using Flat Drill

2.1. Three-Dimensional Shape Representation by Contour Line Model

To calculate the tool paths, the tool position along the surface of the product shape must be calculated based on the interference amount between the product shape and tool. The standard triangulated language (STL) format, in which a surface is represented by a plurality of triangular meshes (as shown in **Fig. 1**), is typically used for three-dimensional (3D) shape information exchange; however, it is not suitable for calculating tool positions

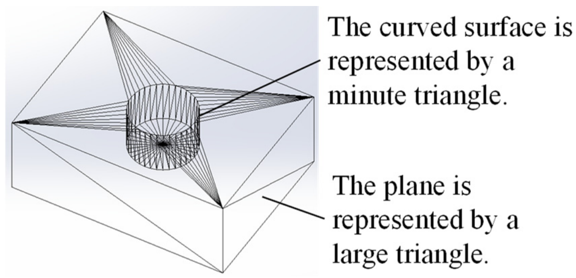


Fig. 1. Standard triangulated language (STL) format.

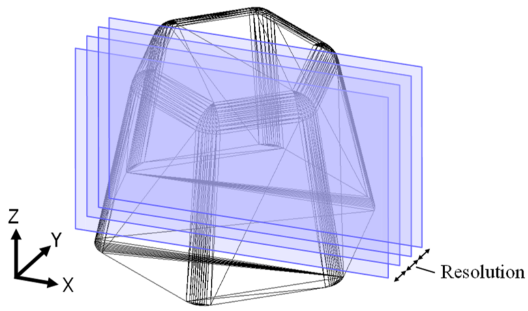


Fig. 2. Product model expressed in STL format segmented finely on *ZX* plane at intervals of the resolution.

or paths. In the STL format, a plane is represented by larger triangular meshes, and a curved surface is represented by smaller triangular meshes to represent surfaces with the minimum number of triangular meshes. Because the triangular mesh size expressed in STL format is non-uniform, the tool position along the surface of the product shape should not be calculated based on the interference amount between the product shape and tool without any modification.

A method known as the contour line model that represents the surface of the product shape as discrete points at intervals below the indicated resolution is proposed herein [25, 26]. The contour line model is a model in which the product model is minutely segmented on the plane along any axial direction, and the contour line of the cross section is superimposed. In the STL format, the triangular mesh size is non-uniform; therefore, the distance between the intersections with the triangular mesh obtained on the segmented plane is not constant. Therefore, the product surface must be represented by points at intervals below the indicated resolution.

The algorithm for the contour line model is described as follows. The product model expressed in STL format is segmented finely on the *ZX* plane at intervals of the indicated resolution, as shown in **Fig. 2**. For each surface of the segmented *ZX* plane, the intersection between the plane and all triangular meshes is geometrically extracted. The line segment, where the triangular mesh and the target plane intersect, are then calculated. The contour line of the segmented plane is calculated by searching for a line with the same start of the end point and connecting the same points, as shown in **Fig. 3**. Subsequently, the line

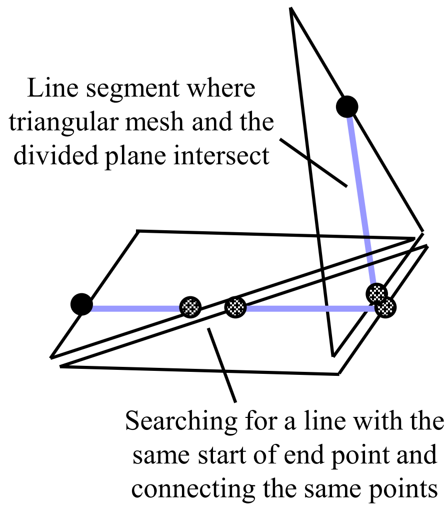


Fig. 3. Geometrical relationship between triangular mesh and the segmented plane.

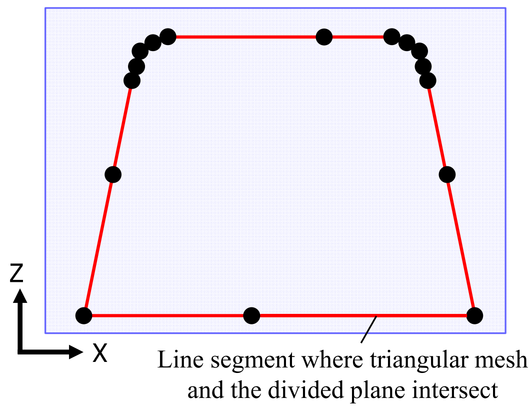


Fig. 4. Contour line obtained from line segment where triangular mesh and segmented plane intersect.

segments composing the obtained contour line are non-uniform in length, as shown in **Fig. 4**. In particular, the plane of a shape is represented by a single long line segment, whereas a curved surface is represented by a plurality of minute line segments. Therefore, when the length of each line segment is longer than the indicated resolution, the points are inserted via linear interpolation. When the length of the line segment obtained from the STL format is less than the indicated resolution, it is expressed using the line segment, as shown in **Fig. 5**. As described above, the product surface expressed by a non-uniform triangular mesh can be expressed by points at intervals below the indicated resolution. The accuracy of this model depends on the maximum value of the tolerance specified when expressing the 3DCAD model in STL format and the indicated resolution of the contour line model.

2.2. Roughing Using a Flat Drill

To calculate the tool path for roughing using a flat drill, the tool paths for the scanning operation were first calcu-

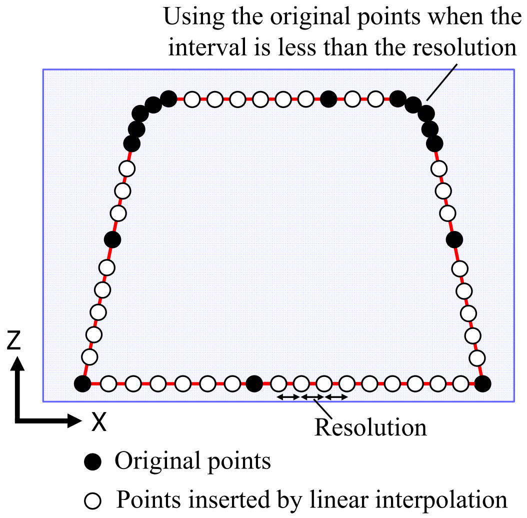


Fig. 5. Contour line expressed by points at intervals below the resolution.

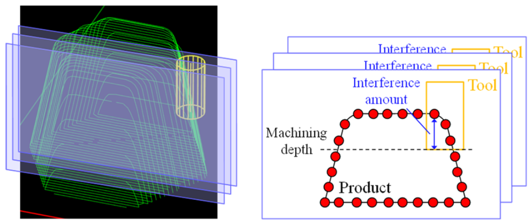


Fig. 6. Description of product and tool with contour line model.

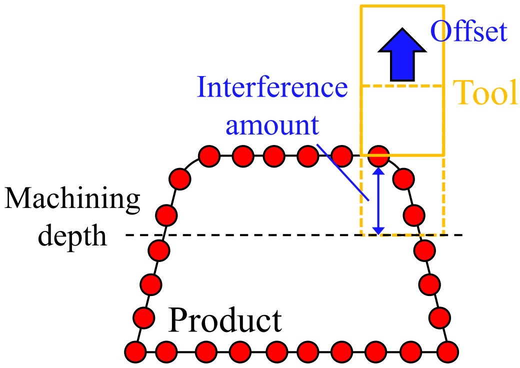


Fig. 7. Tool offset according to calculated interference amount.

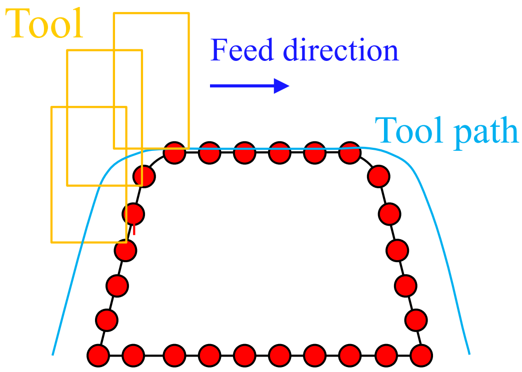


Fig. 8. Tool path obtained by calculating tool position at each minute interval.

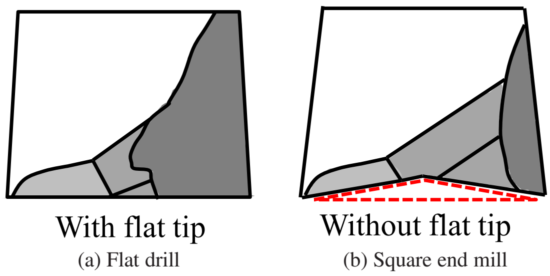


Fig. 9. Comparison of tool shape between flat drill and square end mill.

lated based on the interference amount between the product surface represented by the contour line model and the tool. The tool position can be determined by calculating the interference amount between the product surface and the tool in the Z-axis direction at every minute interval with respect to the tool feed direction and by offsetting the maximum value of the interference amount in the Z-axis direction.

First, the tool was segmented by the planes in the same interval as the product, as shown in **Fig. 6**. In the case of the square end mill, the tool is shown as a rectangle on the plane.

Next, the interference amount on each segmented plane is calculated by detecting the product surface points on the tool, as shown in **Fig. 7**. The maximum interference amount was calculated from the interference amount on each segmented plane. The tool position can be calculated by offsetting the tool in the Z-axis direction by the obtained maximum interference amount. By calculating the tool position at every minute interval with respect to the tool feed direction, the tool path can be calculated as shown in **Fig. 8**. The analysis shows that a machining error generally occurs in the tool radial direction and y-direction. However, the interval of the segmented plane was analyzed at 5 μm in this study. Because the remaining amount of roughing is typically tens to hundreds of micrometers, the machining error is considered acceptable.

When roughing using the flat drill proposed herein, the tool moved only in the Z-axis direction during machining. The tool position for machining with a flat drill can be calculated from the tool position for the scanning operation, as described above. A flat drill is a drill with a flat tip, as shown in **Fig. 9(a)**. Unlike a square end mill, it cannot feed a tool laterally, but it is suitable for machining to feed a tool longitudinally. Based on the advantages of the flat drill, machining troubles such as tool breakages and chatter vibration are expected to be reduced because of the axial sturdiness of the tool.

Furthermore, the flat drill can machine lapped holes that cannot be machined using a normal drill owing to

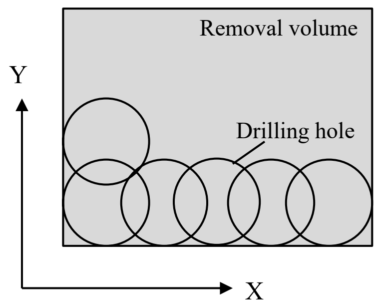


Fig. 10. Drilling multiple holes at constant intervals using a flat drill.

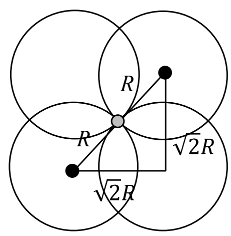


Fig. 11. Interval between centers of holes.

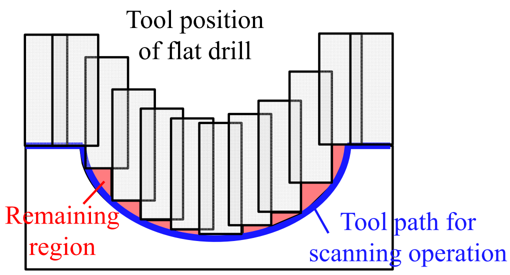


Fig. 12. Tool position of flat drill calculated from tool path for scanning operation.

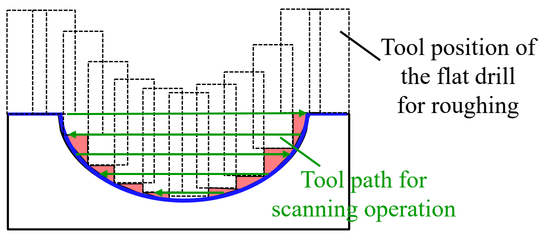


Fig. 13. Scanning operation tool path using semi-finishing tool.

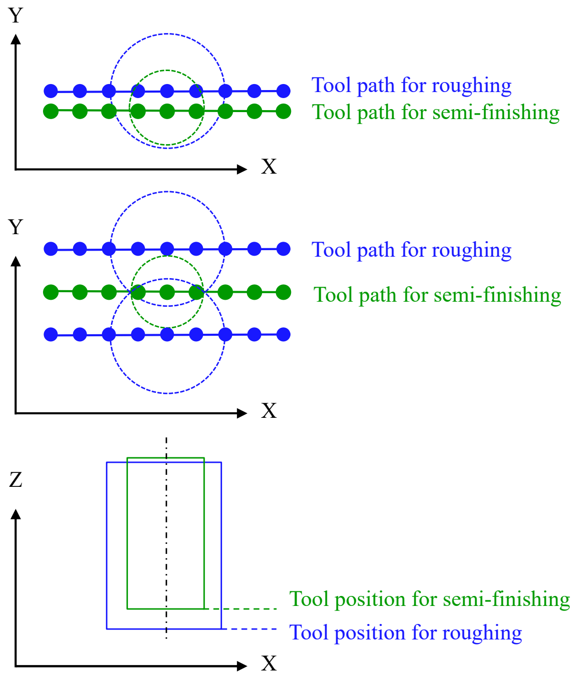


Fig. 14. Positional relationship of tools determined to be inclusive.

its flat tip. Hence, roughing using a flat drill by drilling multiple holes at constant intervals is proposed herein, as shown in **Fig. 10**. The interval between the centers of the holes I_c can be determined as follows to machine without having an uncut region remaining other than the edge, as shown in **Fig. 11**.

$$I_c = \sqrt{2} \times R \quad (R\text{: tool radius}) \qquad (1)$$

The depth of each drilling hole can be determined from the depth calculated based on the tool path for the scanning operation, as shown in **Fig. 12**. The tool position of the flat drill can be calculated by extracting the same position on the X- and Y-axes from the tool path for the scanning operation and using the position of the Z-axis as that of the flat drill.

When roughing using a flat drill, unlike a scanning operation involving a square end mill, a stairs-like region remains (as shown in **Fig. 12**) because flat drill machines are used to feed a tool longitudinally. Generally, finishing cannot be conducted when remaining regions exist, e.g., stairs-like regions, because of the possibility of tool breakage. Therefore, semi-finishing must be conducted by machining gradually using a small axial depth of cut. Subsequently, to avoid increasing the machining time, semi-finishing must be conducted only on the remaining region during roughing. During the semi-finishing, the tool path for the scanning operation involving the semi-finishing tool to machine the entire region was calculated as shown in **Fig. 13**. In the tool path for the scanning operation, the tool positions were calculated at minute intervals in the tool feed direction. Because the tool diameter used for semi-finishing is generally smaller than the tool diameter used for roughing, whether the tool region of each tool position for semi-finishing is included in that of the tool position with roughing must be verified, as shown in **Fig. 14**. If the tool region for semi-finishing is completely included in the tool region for roughing, then it can be regarded as the air cutting region and hence be excluded from the tool path. By verifying all the tool positions, the tool path for semi-finishing, in which the remaining region from roughing is machined, can be calculated.

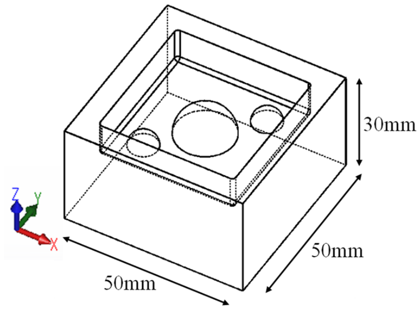


Fig. 15. Product model for case study.

Table 1. Machining conditions for case study.

	Flat drill	Square end mill
Tool diameter	4.0 mm	4.0 mm
Axial depth of cut	–	0.5 mm
Radial depth of cut	2.0 mm	2.0 mm
Machining depth	10 mm	
Spindle speed	10000 min^{-1}	
Feed speed (XY)	300 mm/min	
Feed speed (Z)	50 mm/min	

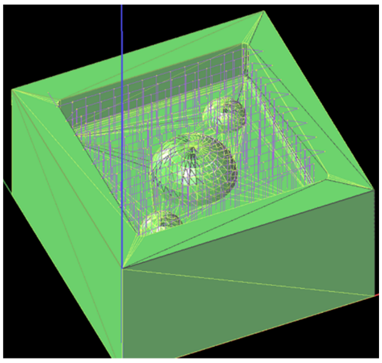


Fig. 16. Tool path generated using flat drill.

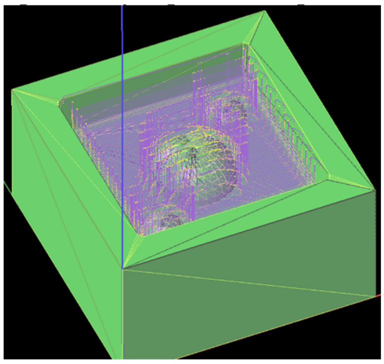


Fig. 17. Tool path generated using square end mill.

Table 2. Machining time comparison between flat drill and square end mill.

	Flat drill	Square end mill
Machining time	66 min 51 s	86 min 10 s

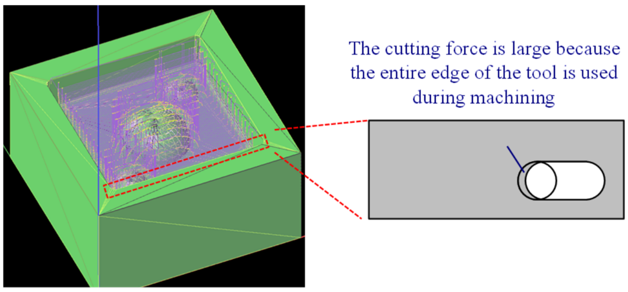


Fig. 18. Tool state at the beginning of machining.

3. Case Study

Two case studies were conducted in this study. The first is to validate the effectiveness of the machining efficiency by comparing the machining time between the proposed roughing using a flat drill and the conventional roughing using a square end mill. The other is to validate the possibility of machining multiple products simultaneously with multiple spindles using the machine tool developed.

3.1. Validation of Effectiveness by Comparing Machining Time Between Flat Drill and Square End Mill

To verify the effectiveness of the proposed method, roughing using a flat drill and a square end mill was performed on the product model, as shown in **Fig. 15**. The machining times of the flat drill and square end mill were compared. When machining using a square end mill, a gradual machining had to be performed in the Z-axis direction because of the weakness of the axial direction cutting of the square end mill. Using the existing CAM software, a tool path can be generated without reducing the machining efficiency by setting the tool approaching angle to the workpiece. However, the user must determine these settings individually. This is one of the reasons that renders it difficult to automate NC program generation. In this case study, the tool path was generated using the machining conditions shown in **Table 1**, assuming that the tool was moving without approaching the angle.

The tool paths generated using the flat drill and square end mill are shown in **Figs. 16** and **17**, respectively. The results of the machining time calculated by the total distance and feed speed are shown in **Table 2**.

When machining using a square end mill, the axial depth of cut cannot be large; furthermore, the total distance will be long because the entire edge of the tool is used in the region, as shown by the broken line in **Fig. 18**, and the cutting force is large. Meanwhile, when machining using the flat drill proposed herein, machining can be performed up to the machining depth in the Z-axis direction continuously at a constant feed speed.

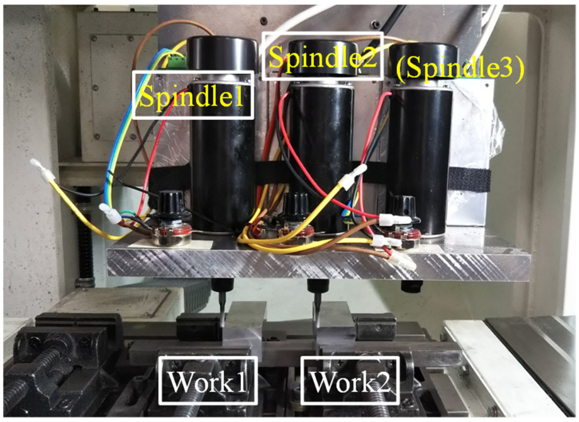


Fig. 19. Prototype machine tool with multiple spindles.

3.2. Validation of Machining Efficiency Using Flat Drill Roughing

In the next case study, to verify the productivity effectiveness of roughing using the flat drill proposed herein, a prototype machine tool with multiple spindles, as shown in **Fig. 19**, was developed. This study verified whether multiple products can be machined simultaneously. Generally, when machining with multiple spindles simultaneously, as shown in **Fig. 19**, it is difficult for the square end mill to perform machining to feed the tool laterally without machining troubles because the cutting force to the spindle is large and the chatter vibration can be large. However, the flat drill can perform machining without machining troubles because it feeds only in the Z-axis direction, which may suppress chatter vibration. This study assumed that the cutting force to the spindle was small, and that the machining trouble due to chatter vibration was negligible during semi-finishing and finishing because the tool had a small diameter and the cutting volume per tool feed per tooth was small during semi-finishing and finishing.

The case study was conducted using the product model, as shown in **Fig. 20**. **Table 3** shows the machining conditions for roughing, semi-finishing, and finishing.

The tool path generated using the proposed method is shown in **Fig. 21**. The results obtained using the generated tool path for each process are shown in **Figs. 22(a)–(c)**. When roughing using the flat drill, it was confirmed that the work material did not chatter and vibrate during machining, and that the machining was completed without machining troubles. Furthermore, it was confirmed that the workpiece shape after machining was favorable, as shown in **Fig. 22(a)**. When semi-finishing after roughing, it was confirmed that the generated tool path was valid because no machining troubles such as tool breakage occurred. Finally, it was confirmed that the finishing was completed with the intended machining accuracy based on the workpiece shape, as shown in **Fig. 22(c)**. **Table 4** shows that the machining time for each process was appropriate.

As described above, roughing using a flat drill enables

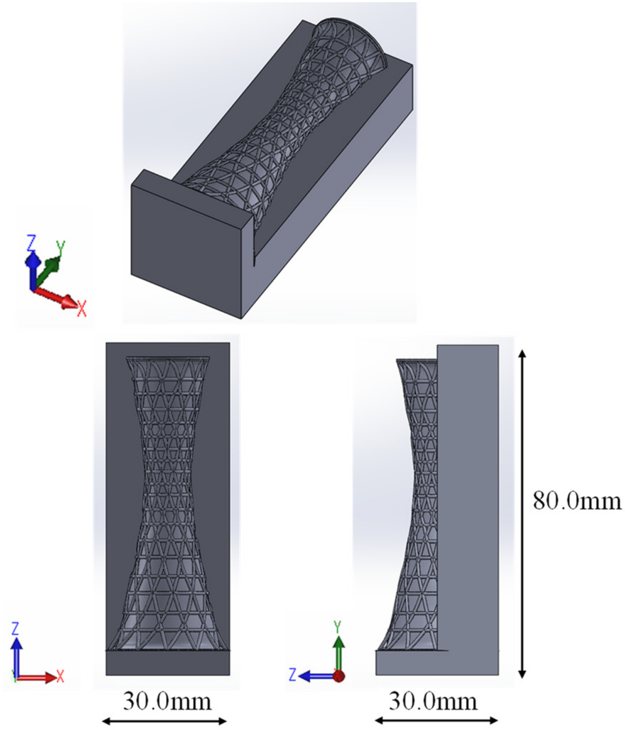


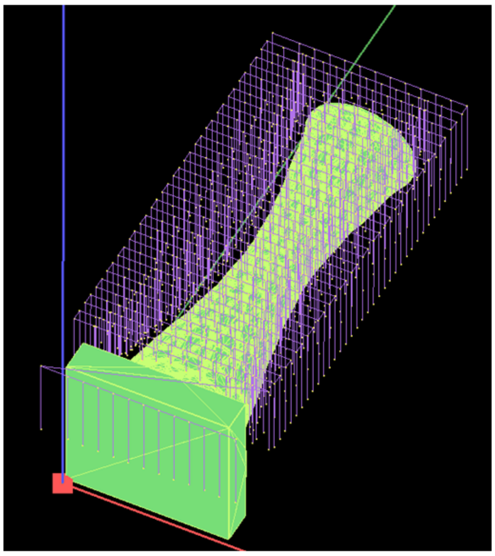
Fig. 20. Product model for case study.

Table 3. Machining conditions for case study.

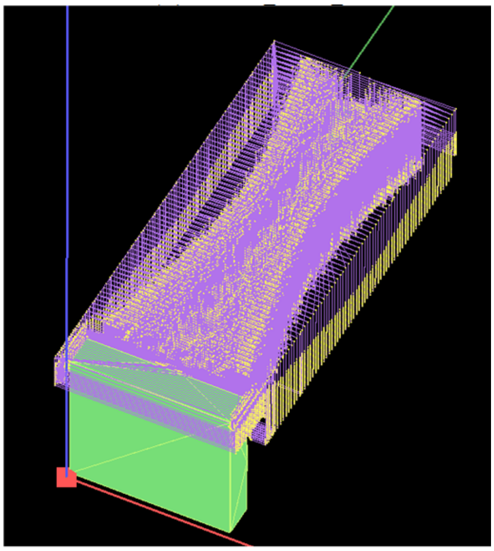
	Rough	Semi-Finish	Finish
Workpiece material	A7075		
Tool type	Flat drill	Ball end mill	
Tool diameter	4.0 mm	2.0 mm	
Axial depth of cut	–	0.5 mm	–
Radial depth of cut	2.0 mm	0.5 mm	0.1 mm
Spindle speed	10000 min^{-1}		
Feed speed (XY)	–	300 mm/min	
Feed speed (Z)	50 mm/min		

not only machining troubles to be suppressed and the machining efficiency to be improved when machining one product, but also enables multiple products to be machined simultaneously with multiple spindles. However, the proposed method has several disadvantages and limitations, as follows.

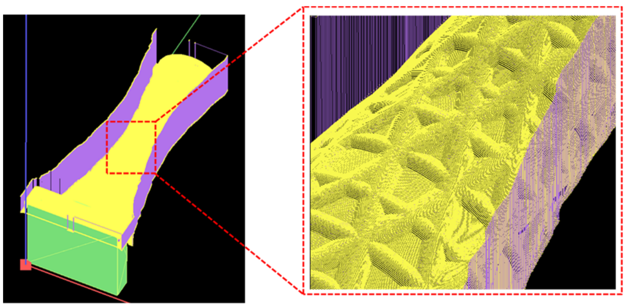
- If the total machining depth is small, then the normal scanning operation with a square end mill may have a shorter machining time because the horizontal tool feed speed is higher.
- Because machining with a flat drill increases the spindle torque, a machine with a large spindle torque is necessary when a tool with a large diameter is used.
- When the product shape is complicated, because the work material after roughing using a flat drill com-



(a) Roughing



(b) Semi-finishing

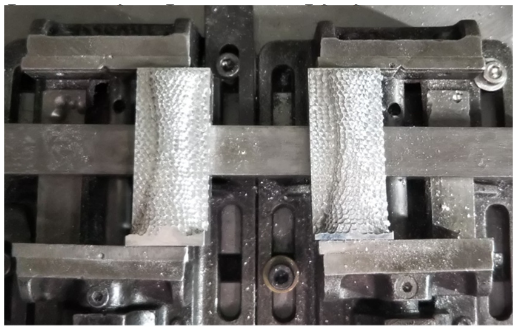


(c) Finishing

Fig. 21. Tool path generated using proposed method.

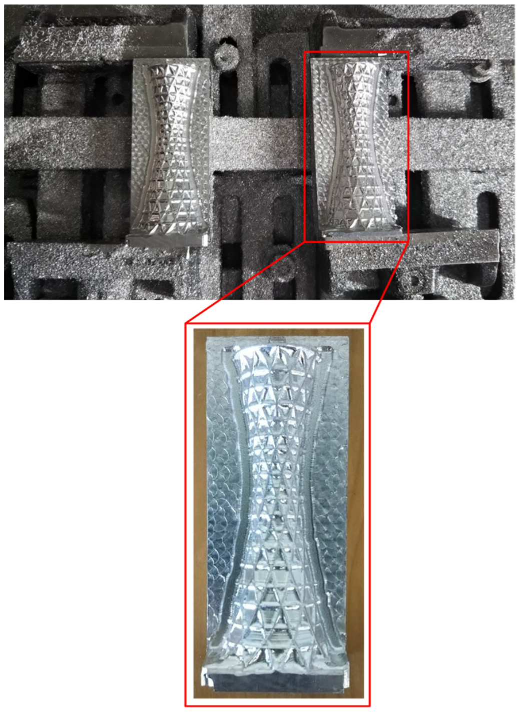
prises stepwise residual margins, the total machining time may be long owing to the removal of these margins in semi-finishing.

Nevertheless, the results indicate the possibility of significantly improving the machining efficiency in the limited production of diversified products.



(a) Roughing

(b) Semi-finishing



(c) Finishing

Fig. 22. Results of machining using generated tool path for each process.

Table 4. Results of machining time of each process.

	Machining time
Roughing	2 h 39 min
Semi-finishing	1 h 49 min
Finishing	3 h 01 min

4. Conclusions

A method to calculate tool paths for roughing using a flat drill from a 3DCAD model represented by the STL format of the product was proposed herein. This findings of this study are as follows.

1. A 3D shape can be expressed by superimposing the contour line of the cross sections obtained by segmenting the product along any axial direction.

2. The tool path for roughing with a flat drill can be calculated based on the tool position for the scanning operation. Furthermore, the tool path for semi-finishing only on the remaining region from roughing can be calculated.

3. The results of the machining experiment indicated that the proposed method enabled not only machining troubles to be suppressed and the machining efficiency to be improved when machining one product, but also enabled multiple products to be machined simultaneously with multiple spindles.

Acknowledgements

This work was partially supported by the Tateishi Science and Technology Foundation, Osawa Scientific Studies Grants Foundation, Suzuki Foundation, Kawanishi Memorial ShinMaywa Education Foundation, and Mazak Foundation.

References:

[1] K. Nakamoto, K. Shirase, H. Wakamatsu, A. Tsumaya, and E. Arai, "Development of Digital Copy Milling System to Realize NC Programless Machining: 3rd Report, Machining Strategy for In-Process Adaptation of Cutting Conditions," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.69, No.677, pp. 270-277, 2003.

[2] K. Shirase and K. Nakamoto, "Direct Machining Operation Performed by Autonomous NC Machine Tool Controlled by Digital Copy Milling Concept," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.74, No.743, pp. 1901-1906, 2008.

[3] K. Shirase and K. Nakamoto, "Simulation Technologies for the Development of an Autonomous and Intelligent machine Tool," Int. J. Automation Technol., Vol.7, No.1, pp. 6-15, 2013.

[4] K. Shirase, T. Kondo, M. Okamoto, H. Wakamatsu, and E. Arai, "Development of Virtual Copy Milling System to Realize NC Programless Machining: Real Time Tool Path Generation for Autonomous NC Machine Tool," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.66, No.644, pp. 298-303, 1999.

[5] D. Hamada, K. Nakamoto, T. Ishida, and Y. Takeuchi, "Development of CAPP system for multi-tasking machine tool," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.78, No.791, pp. 2698-2709, 2012 (in Japanese).

[6] L. Wang, M. Holm, and G. Adamson, "Embedding a process plan in function blocks for adaptive machining," CIRP Annals – Manufacturing Technology, Vol.59, Issue 1, pp. 433-436, 2010.

[7] Y. Woo, E. Wang, Y. S. Kim, and H. M. Rho, "A hybrid feature recognizer for machining process planning systems," CIRP Annals – Manufacturing Technology, Vol.54, Issue 1, pp. 397-400, 2005.

[8] K. Nakamoto, K. Shirase, H. Wakamatsu, A. Tsumaya, and E. Arai, "Automatic production planning system to achieve flexible direct machining," JSME Int. J. Series C, Vol.47, No.1, pp. 136-143, 2004.

[9] A. Ueno and K. Nakamoto, "Proposal of machining features for CAPP system for multi-tasking machine tools," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.81, No.825, doi: 10.1299/transjsme.15-00108, 2015 (in Japanese).

[10] E. Morinaga, M. Yamada, H. Wakamatsu, and E. Arai, "Flexible process planning method for milling," Int. J. Automation Technol., Vol.5, No.5, pp. 700-707, 2011.

[11] E. Morinaga, T. Hara, H. Joko, H. Wakamatsu, and E. Arai, "Improvement of computational efficiency in flexible computer-aided process planning," Int. J. Automation Technol., Vol.8, No.3, pp. 396-405, 2014.

[12] K. Dwijayanti and H. Aoyama, "Basic study on process planning for turning-milling center based on machining feature recognition," J. of Advanced Mechanical Design, Systems and Manufacturing, Vol.8, No.4, JAMDSM0058, 2014.

[13] H. Sakurai and P. Dave, "Volume decomposition and feature recognition, part 1 – polyhedral objects," Computer-Aided Design, Vol.27, Issue 11, pp. 793-869, 1995.

[14] H. Sakurai and P. Dave, "Volume decomposition and feature recognition, part II – curved objects," Computer-Aided Design, Vol.28, Issues 6-7, pp. 519-537, 1996.

[15] T. Inoue and K. Nakamoto, "Proposal of a recognition method of machining features in computer aided process planning system for complex parts machining," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.83, No.850, doi: 10.1299/transjsme.16-00574, 2017 (in Japanese).

[16] M. M. Isnaini, Y. Shinoki, R. Sato, and K. Shirase, "Development of a CAD-CAM interaction system to generate a flexible machining process plan," Int. J. Automation Technol., Vol.9, No.2, pp. 104-114, 2015.

[17] I. Nishida, R. Sato, and K. Shirase, "Proposal of process planning system for end-milling operation considering product design constraints," The Institute of Systems, Control and Information Engineering, Vol.30, No.3, pp. 81-86, 2017 (in Japanese).

[18] I. Nishida, T. Hirai, R. Sato, and K. Shirase, "Automatic process planning system for end-milling operation considering CAM operator's intention," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.84, No.860, doi: 10.1299/transjsme.17-00563, 2018 (in Japanese).

[19] I. Nishida and K. Shirase, "Automated process planning system for end-milling operation considering constraints of operation (1st report Process planning to minimize the number of times of tool change)," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.84, No.866, doi: 10.1299/transjsme.18-00242, 2018 (in Japanese).

[20] Y. Shinoki, M. M. Isnaini, R. Sato, and K. Shirase, "Machining operation planning system which utilize past machining operation data to generate new NC program," Trans. of the Japan Society of Mechanical Engineers Series C, Vol.81, No.832, 15-00280, 2015 (in Japanese).

[21] M. El-Mehalawi and R. A. Miller, "A database system of mechanical components based on geometric and topological similarity. Part I: representation," Computer-Aided Design, Vol.35, No.1, pp. 83-94, 2003.

[22] M. El-Mehalawi and R. A. Miller, "A database system of mechanical components based on geometric and topological similarity. Part II: indexing, retrieval, matching and similarity assessment," Computer-Aided Design, Vol.35, No.1, pp. 95-105, 2003.

[23] S. Kobayashi, "Present and future of case-based reasoning," J. of Japanese Society for Artificial Intelligence, Vol.7, No.4, pp. 559-566, 1992 (in Japanese).

[24] I. Nishida and K. Shirase, "Automatic Determination of Cutting Conditions for NC Program Generation by Reusing Machining Case Data based on Geometric Properties of Removal Volume," J. of Advanced Mechanical Design, Systems, and Manufacturing, Vol.12, No.4, doi: 10.1299/jamdsm.2018jamdsm0093, 2018.

[25] I. Nishida and K. Shirase, "Proposal of contour line model for high-speed end milling simulation," Int. J. Automation Technol., Vol.14, No.1, pp. 38-45, 2020.

[26] I. Nishida and K. Shirase, "Machining time reduction by tool path modification to eliminate air cutting motion for end milling operation," Int. J. Automation Technol., Vol.14, No.3, pp. 459-466, 2020.

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• "Machine tool assignment realized by automated NC program generation and machining time prediction," Int. J. Automation Technol., Vol.13, No.5, pp. 700-707, 2019.
• "Sequence planning of on-machine measurement and re-machining," J. of Advanced Mechanical Design, Systems, and Manufacturing, Vol.13, No.1, JAMDSM0014, 2019.

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• T. Kobayashi, T. Hirooka, A. Hakotani, R. Sato, and K. Shirase, "Tool Motion Control Referring to Voxel Information of Removal Volume Voxel Model to Achieve Autonomous Milling Operation," Int. J. Automation Technol., Vol.8, No.6, pp. 792-800, 2014.
• M. M. Isnaini, Y. Shinoki, R. Sato, and K. Shirase, "Development of CAD-CAM Interaction System to Generate a Flexible Machining Process Plan," Int. J. Automation Technol., Vol.9, No.2, pp. 104-114, 2015.
• K. Shirase, "CAM-CNC integration for innovative intelligent machine tool," Proc. of the 8th Int. Conf. on Leading Edge Manufacturing in 21st Century (LEM21), A01, 2015.
• I. Nishida, R. Okumura, R. Sato, and K. Shirase, "Cutting Force Simulation in Minute Time Resolution for Ball End Milling Under Various Tool Posture," ASME J. of Manufacturing Science and Engineering, Vol.140, No.2, 021009, 2018.

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