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Paper:

Machining Time Reduction by Tool Path Modification to Eliminate Air Cutting Motion for End Milling Operation

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A method to uniquely calculate the tool path and to modify the tool path during air cutting motion to reduce the machining time is proposed. This study presents a contour line model, in which the product model is minutely divided on a plane along an axial direction, and the contour line of the cross-section of the product is superimposed. A method is then proposed to calculate the tool position according to the degree of interference between the product surface and the tool. Furthermore, this study proposes a technique to reduce the machining time by tool path modification during air cutting motion. This is determined by the geometric relationship between the product surface and the tool, and not based on cutting simulations. A cutting experiment was conducted to validate the effectiveness of the proposed method. Based on the results, it was confirmed that the difference in machining time between the tool path with modification and the tool path without modification was large. Moreover, the machining time was significantly reduced by the tool path modification. The results showed that the proposed method has good potential to perform customized manufacturing, and to realize both high productivity and reliability in machining operation.

Keywords: CAM, end milling, machining time reduction, air cutting motion, NC machining

1. Introduction

Flexible manufacturing or customized manufacturing is required for the machining of dies and molds for medical implants. The time and cost associated with preparation tasks such as numerical control (NC) program generation greatly affect the production efficiency in flexible manufacturing or customized manufacturing. There are several previous studies that investigated different techniques for reducing the time for NC program generation [1–4]. Furthermore, the reduction of the machining time for NC machine tools contributes significantly to the improvement of production efficiency, even in flexible manufacturing or customized manufacturing. There are previous studies on the reduction of machining time that avert the challenges of tool breakage by measuring or predicting the cutting force during machining, and modifying the cutting conditions according to the magnitude of the cutting force [5–9]. An instantaneous rigid force model [10–13] is widely used to predict the cutting forces for end milling operation. This method requires that the uncut chip thickness is accurately known to predict the cutting force. The Z-map model [14–16], which discretely represents a workpiece with a plurality of lines in the Z-axis direction arranged at equal intervals on the XY-plane, has also been proposed. The voxel model [17–22], which discretely represents the inside of a workpiece using a cube called a voxel, has been investigated by several researchers. However, both models require a long simulation time, therefore, a long processing time is required to generate an NC program. Particularly, in customized production, the preparation time greatly affects the production efficiency. Therefore, the reduction of time for the cutting simulation directly affects the improvement of production efficiency. Furthermore, in previous studies, tool paths are generated by commercial CAM software, and it is difficult to improve machining efficiency by modifying the tool paths because of reliability considerations. It is necessary to automatically generate an NC program without CAM operation to improve the preparation tasks and the machining efficiency, such as the instructions for the target machined surface.

This study proposes a method to automatically generate tool paths based only on the 3DCAD model, and to modify the tool paths to eliminate air cutting motion for the reduction of the machining time. First, this study proposes a new 3D representation model called a contour line model, in which the product model is minutely divided on a plane along an axial direction, and the contour line of the cross-section of the product is superimposed. Subsequently, a method is presented to calculate the tool positions according to the degree of interference between the product surface and the tool. This facilitates the automatic generation of the tool path that traces the product surface, even if the product consists of complex surfaces. Furthermore, this study proposes a method to reduce machining time by modifying tool paths during air cutting motion. This information is obtained based on the geometric relationship between the product surface and tool without using a cutting simulation. A cutting experiment

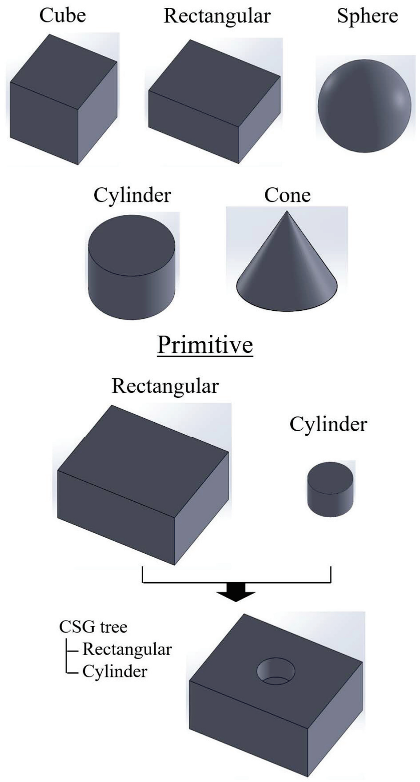


Fig. 1. Constructive solid geometry (CSG) model.

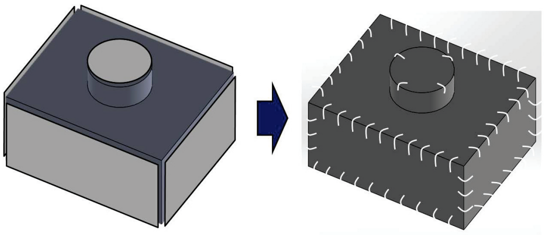


Fig. 2. Boundary representation (B-rep) model.

is conducted to validate the effectiveness of the proposed method.

2. Tool Path Generation Using the Contour Line Model

2.1. Three-Dimensional Shape Representation Using the Contour Line Model

The constructive solid geometry (CSG) and boundary representation (B-rep) models are shown in **Figs. 1** and **2** as representative models of three-dimensional shapes. In the CSG model, a complex shape can be represented visually by combining basic three-dimensional shapes (such as cubes, rectangles, spheres, etc.) called primitives. In the B-rep model, a complex shape can be represented by connecting the boundary surfaces between an object and its surroundings. To calculate the tool path, it is necessary to determine the tool position along the surface of

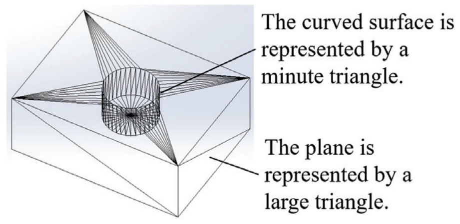


Fig. 3. Standard triangulated language (STL) format.

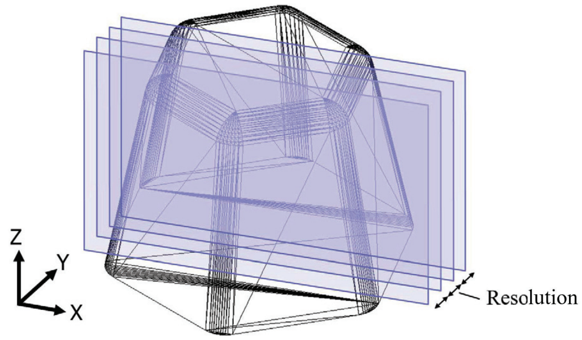


Fig. 4. Product model represented in STL format, finely divided on the ZX-plane at intervals corresponding to the resolution.

the product shape due to the degree of interference between the product shape and tool. Standard triangulated language (STL) format, in which a surface is represented by a plurality of triangular meshes as shown in **Fig. 3**, is commonly used for 3D shape information exchange. However, it is not suitable for the calculation of tool positions or paths. In the STL format, a plane is represented by large triangular meshes, whereas a curved surface is represented by much smaller triangular meshes, to represent surfaces using the minimum number of these meshes. Given that the triangular mesh size represented in STL format is non-uniform, it is not suitable for the calculation of the tool position along the surface of the product shape due to the degree of interference between the product shape and tool.

This study proposes a new method called the contour line model, which represents the surface of the product shape as discrete points at intervals below the indicated resolution. In the contour line model, the product model is minutely divided on a plane along an 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 using the triangular mesh obtained on the divided plane is not constant. Therefore, the product surface needs to be represented by points at intervals below the indicated resolution.

The algorithm for the contour line model is described as follows. The product model represented in STL format is finely divided on the ZX-plane at intervals for the indicated resolution, as shown in **Fig. 4**. For each surface of the divided ZX-plane, the intersection between the

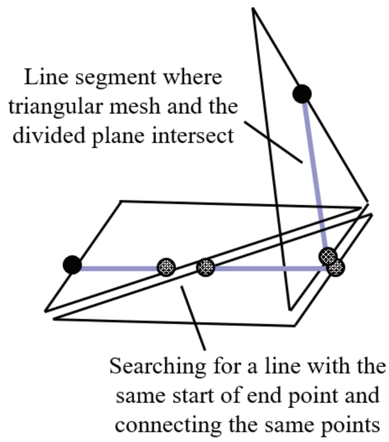


Fig. 5. Geometrical relationship between triangular mesh and the divided plane.

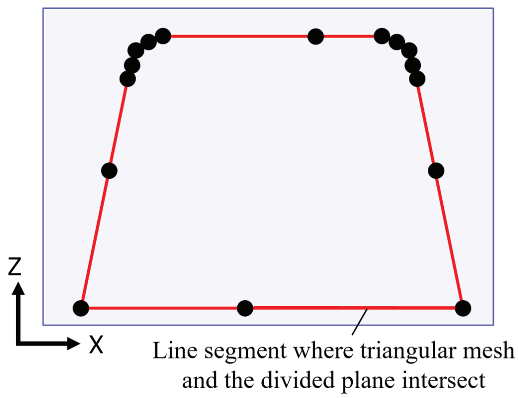


Fig. 6. Contour line obtained from the line segment where triangular mesh and the divided plane intersect.

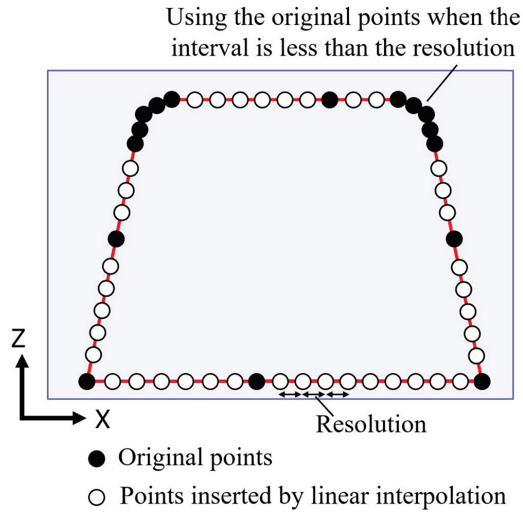


Fig. 7. Contour line expressed by points at intervals below the resolution.

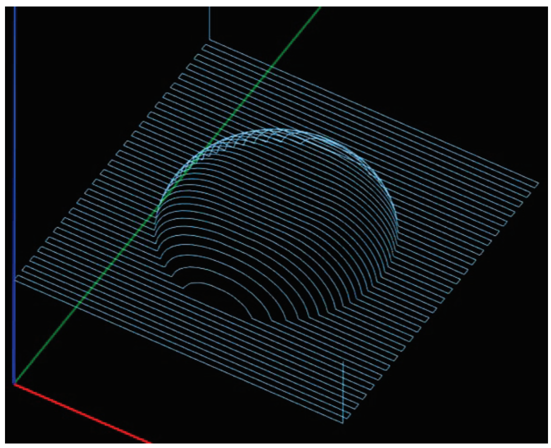


Fig. 8. Example of scanning tool paths (zigzag).

plane and all triangular mesh is geometrically extracted. The line segment where the triangular mesh and the target plane intersect is calculated. The contour line of the divided plane is calculated by searching for a line with the same start of the endpoint and connecting the same points, as shown in **Fig. 5**. The line segments that consist of the obtained contour line have a non-uniform length, as shown in **Fig. 6**. In particular, a plane of the 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 using linear interpolation. When the length of the line segment obtained using the STL format is less than the indicated resolution, it is expressed using the line segment as shown in **Fig. 7**. As previously described, the product surface expressed by a non-uniform triangular mesh can be represented 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, in addition to the indicated resolution of the contour line model.

2.2. Tool Path Generation for the Scanning Operation

The scanning operation is widely used in machining, especially in finishing, as shown in **Fig. 8**. This operation is performed in a bi-direction (zigzag) or a mono-direction along the product surface. The tool paths for scanning operation are easy to calculate by considering only the offset of the *Z*-axis direction along the tool feed direction of the product surface.

In this study, the tool paths for scanning operation are calculated by the degree of interference between the product surface, represented by the contour line model that is previously described, and the tool. In a scanning operation, the step over is uniquely determined by the radial depth of cut. Therefore, the tool position can be determined by calculating the degree of interference between the product surface and the tool in the *Z*-axis direction at every minute interval with respect to the tool feed direction, and offsetting the maximum value of the degree of interference in the *Z*-axis direction.

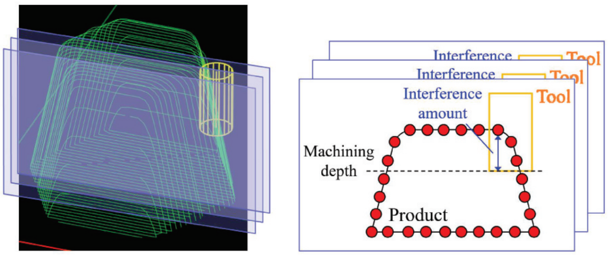


Fig. 9. Description of product and tool with contour line model.

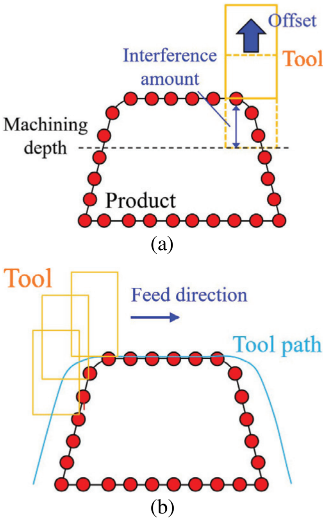


Fig. 10. (a) Tool offset according to the calculated degree of interference. (b) Tool path obtained by calculating the tool position at one-minute intervals.

First, the tool is divided by the planes with the same interval as the product, as shown in **Fig. 9**. In the case of the square end mill, the tool is represented as a rectangle on the plane.

Next, the degree of interference on each divided plane is calculated by detecting the product surface points that exist in the tool as shown in **Fig. 10(a)**. The maximum value of the degree of interference is calculated from the extent of the interference on each divided plane. The tool position can be calculated by offsetting the tool in the Z-axis direction by the maximum degree of interference. By calculating the tool position at intervals of one minute with respect to the tool feed direction, the tool path can be calculated as shown in **Fig. 10(b)**.

The proposed model facilitates analysis by approximating a square end mill to a cylinder as previously described. The proposed model can also be used to analyze other tools by representing them as the superposition of square end mills. For example, in the case of a ball end mill, the tool can be discretely represented using a plurality of square end mills in which the tool diameter is decreased to represent the tool tip, as shown in **Fig. 11**. The interference area between the tool and the product can be calculated by repeating in order from the largest tool diameter for a plurality of discretely expressed square end mills.

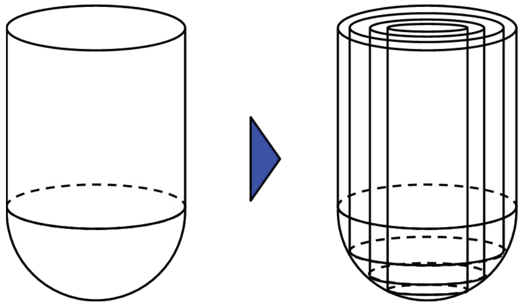


Fig. 11. Ball end mill expressed by the superposition of square end mills.

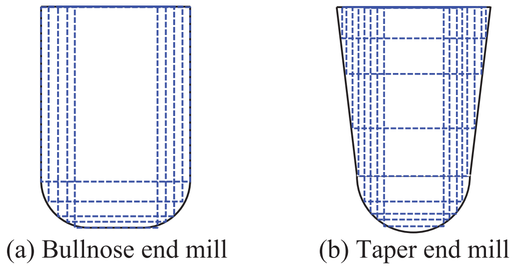


Fig. 12. Example of representation using various tools.

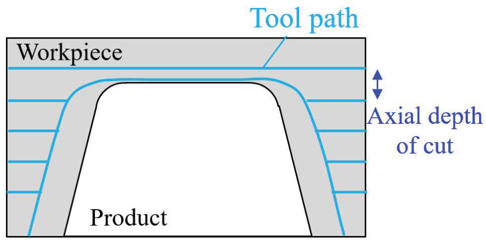


Fig. 13. Scanning tool paths for roughing operation.

Furthermore, the various tool shapes such as the bullnose end mill and the tapered end mill can also be represented by multiple square end mills, as shown in **Fig. 12**.

3. Machining Time Reduction by Modifying the Tool Path

In the case of roughing operation, the tool path goes gradually down in the negative direction of the Z-axis from the upper surface of the workpiece using the axial depth of the cut, as shown in **Fig. 13**. In this case, as the machining depth increases, the air cutting motion along the product shape becomes larger as shown in **Fig. 14**. It is necessary to reduce the distance or increase the tool feed speed in the air cutting motion to improve machining efficiency. In previous studies [8, 9], a method has been proposed to control the tool feed speed according to the cutting forces predicted by cutting simulations. In these works, the machining time is reduced by adapting the tool feed speed in the air cutting motion. However, in previous methods, the tool paths are not modified to reduce the dis-

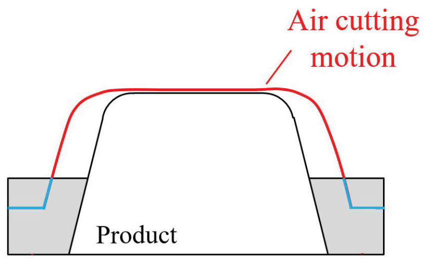


Fig. 14. Air cutting motion in roughing operation.

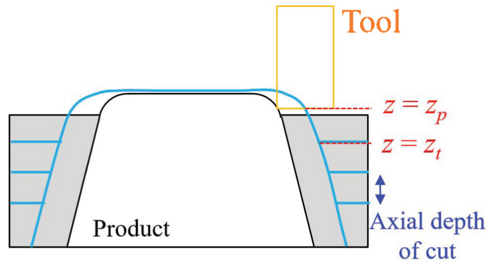


Fig. 15. Extraction of air cutting motion according to the characteristics of the tool path.

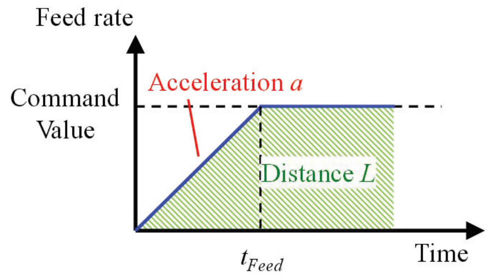


Fig. 16. Relationship between feed rate, acceleration, and distance for tool feed motion.

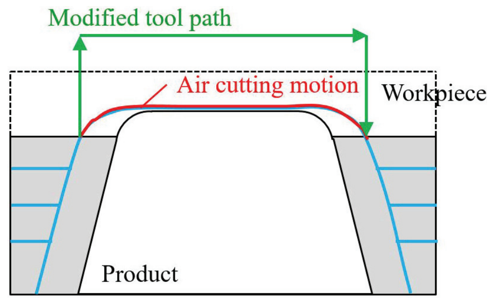


Fig. 17. Modified tool path to avoid air cutting motion for improvement of machining efficiency.

tance in air cutting motion. As such, the actual tool feed speed is lower than the command value when the acceleration of the feed axis of the machine tool is insufficient to precisely follow the product surface. Therefore, this study proposes a method to reduce machining time by modifying the tool paths to avoid air cutting motion, even if the acceleration of the feed axis of the machine tool is insufficient.

First, a method to extract the air cutting motion is introduced. In the roughing operation, the tool paths are sequentially calculated for each machining depth based on the workpiece surface as shown in **Fig. 13**. In the tool path of each machining depth, the air cutting motion can be determined when the degree of interference between the product and the tool is larger than the axial depth of cut as shown in **Fig. 15**. This is because the region for which the tool position is higher than the target machining position must already be machined. Therefore, the air cutting motion can be determined when the Z value of the tool position Z_p, which is obtained by calculating the degree of interference for the machining depth Z_t, satisfies the following equation. In the equation, the axial depth of cut is described as A_d.

$$Z_p > Z_t + A_d \quad \text{. . . . .} \quad (1)$$

Next, a modification of the tool path is introduced to avoid air cutting motion to reduce the machining time. The actual tool feed speed depends on the acceleration of the tool feed axis. A certain amount of time is required for the tool feed speed to reach the command value, as shown in **Fig. 16**. Therefore, the actual tool feed speed does not reach the command value when the tool feed direction changes finely. As a result, the reduction in machining time is insufficient if the command tool feed speed is simply increased, especially when the product shape is complicated. This study modifies the tool path to move straightly toward the Z retracting position on the upper surface of the workpiece, and return to cutting motion to avoid the air cutting motion. This results in a reduction of the influence of the feed axis acceleration as shown in **Fig. 17**. If the distance for the air cutting motion is reduced, this avoidance motion will take a longer time. Therefore, the tool path should be modified only when the distance for the air cut motion is longer than a specific length. As previously described, the machining time can be reduced by generating tool paths to avoid air cutting motion.

4. Case Study

First, tool path generation for the roughing operation was performed on the three-dimensional shape to validate the method to calculate the tool path based on the contour line model as described in Section 2. Next, the roughing operation was conducted, and machining time was compared for the cases of before and after tool path modification. This was done to validate the machining time reduction using the proposed method for avoiding air cutting motion, as described in Section 3. The machining test was performed using a vertical machining center.

4.1. Validation of Tool Path Generation Using a Contour Line Model

First, the scanning tool paths for the roughing operation were calculated for a three-dimensional shape as shown

Fig. 18. 3D CAD model for case study.

Fig. 19. Original shape for case study.

Table 1. Cutting conditions for case study.

Tool type	Ball end mill
Tool diameter	2.0 mm
Axial depth of cut	1.5 mm
Radial depth of cut	0.5 mm
Machining depth	20 mm
Spindle speed	10000 min^{-1}
Feed speed (G01)	900 mm/min
Rapid feed speed (G00)	60,000 mm/min

in **Fig. 18**. This was done to validate the proposed method for generating the tool paths using the contour line model. The three-dimensional model represented in the STL format as shown in **Fig. 18** is a target shape. The image of this original shape is shown in **Fig. 19**, and the three-dimensional model is generated using a three-dimensional scanner (Shining 3D, EinScan-SE). The tool path was calculated using the cutting conditions shown in **Table 1**.

The generated tool paths are shown in **Fig. 20**. The machining test using a chemical wood as a workpiece is performed using a vertical type machining center (XrossCut, Kitamura Machinery Co., Ltd.; CNC: M800/M80 Series, Mitsubishi Electric Co., Ltd.). The result obtained for the machined workpiece is shown in **Fig. 21**. As a result, the tool path generation using the contour line model was validated.

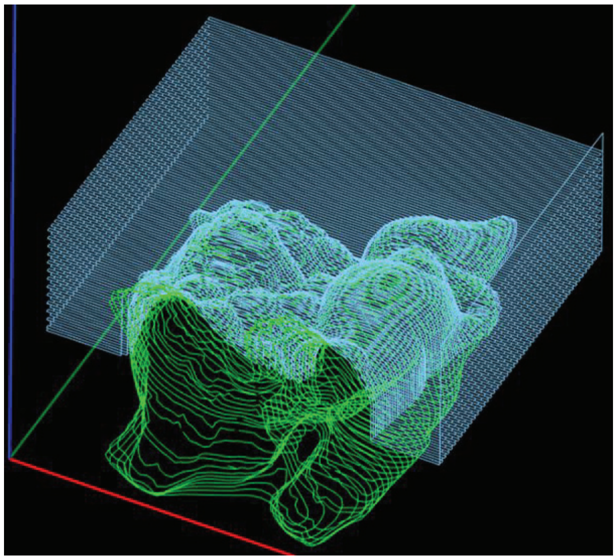


Fig. 20. Tool paths generated using the contour line model.

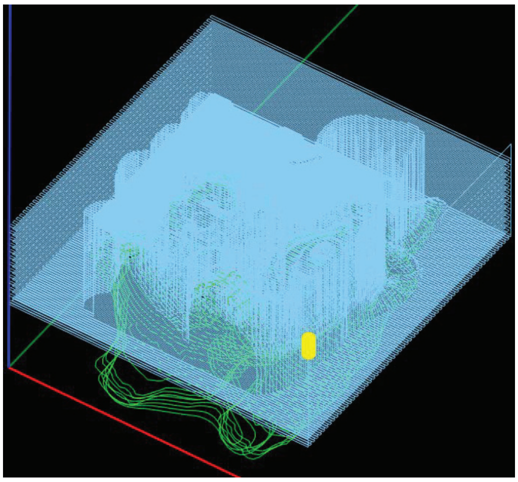
Fig. 21. Workpiece after machining.

4.2. Validation of Machining Time Reduction by Tool Path Modification

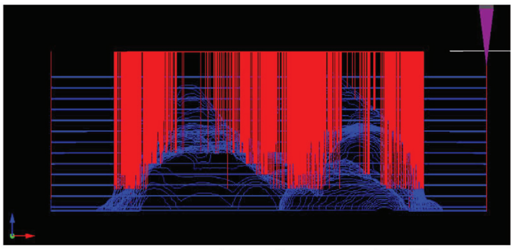
The roughing operation of the three-dimensional shape was conducted to compare machining times for before and after tool path modification. This was done to validate the reduction of the machining time using the proposed method for avoiding air cutting motion. The three-dimensional model shown in **Fig. 18** was used. In addition, the cutting conditions are shown in **Table 1**. The tool path is modified when the distance for the air cutting motion is longer than 10% of the X-axis length of the workpiece.

The tool paths after modification are shown in **Fig. 22**. To avoid the air cutting motion, the tool path is modified to move straightly at the Z retracting position on the upper surface of the workpiece. The distance to avoid the air cutting motion becomes longer as the machining depth increases.

A machining test was performed using NC programs generated before and after tool path modifications, and the two machining times were compared. For the NC program generated after tool paths modification, the tool feed motion to avoid the air cutting motion was commanded



(a) Tool path after modification



(b) Side view of modified tool paths

Fig. 22. Modified tool paths to avoid air cutting motion.

Table 2. Comparison of machining time and actual machining distance before and after tool path modification.

	After modification	Before modification
Machining time	127 min 20 s	507 min 21 s
Actual machining distance	80,008 mm	96,573 mm

by G00 or by the rapid feed motion. The results of machining times and actual machining distance are shown in **Table 2**. Based on the results, the difference in machining time for the cases of before and after tool path modification was large. The effectiveness of the proposed method was successfully validated.

5. Conclusions

This study proposed a method to calculate tool paths using a three-dimensional CAD model represented in STL format, and to modify the tool paths to avoid air cutting motion for the reduction of the machining time. The main findings of this study are as follows.

1. A three-dimensional shape can be expressed by superimposing the contour line of the cross-sections obtained by dividing the product along any axial direction.
2. The tool path for scanning can be calculated by determining the tool position from the degree of interference between the product and the tool.
3. Machining time can be reduced by modifying the tool path to move straightly at the Z retracting position on the upper surface of the workpiece to avoid air cutting motion.

It was confirmed that the tool paths obtained using the proposed method based on a contour line model were valid in several machining tests. Furthermore, it was confirmed that the reduction of the machining time can be achieved by modifying the tool paths to avoid air cutting motion.

Acknowledgements

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Main Works:
• "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.
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