1. Introduction

The automation of machining has been spread rapidly since NC machine tool was introduced. An NC machine tool is operated by a numerical control program called NC program. However, enormous manual tasks to generate NC program, such as the determination of removal volume, machining sequence and cutting conditions, are required for operators. On the other hand, the manufacturing system is changing drastically to the manufacturing of a wide variety of products in small quantities under the rapid change of the customer demand and the diversification of the market requirements. Additionally, many mechanical parts with complicated shapes have been manufactured in aerospace, medical industries and so on. Therefore, the machining processes have been faced the problem to take much time and effort for generating NC programs even using CAM systems. Although a CAM system becomes familiar for generating NC programs, the high-efficiency to generate NC programs has not been realized. A conventional CAM system still requires enormous manual tasks such as decision of the removal volume, the machining sequence and cutting conditions. There are some previous researches on Computer Aided Process Planning (CAPP) systems to automatically determine the machining sequence from CAD model (Sugimura, 2006, Hamada et al., 2012, Ueno and Nakamoto, 2015, Morinaga et al., 2011, Dwijayanti and Aoyama, 2014, Nishida et al., 2017). Furthermore, there is a previous research to automatically generate NC program by determining cutting conditions depending on the product feature (Shinoki et al., 2015). In the previous researches, the cutting conditions are determined by reusing machining case data based on the concept of Case-Based Reasoning (CBR) in order to reflect the experience and the know-how of skillful operators in NC program generation. CBR is the method to solve a new problem by referring to the solution of the past...
similar problem. It is expected that the experience and the know-how in past cases are reflected (Kobayashi, 1992). In such a method to reuse machining case data, it becomes important to design the information to be stored in database. Shinoki et al. (2015) proposed the method to store and refer machining case data for the reuse by recognizing the most similar machining case data. In the recognition of the machining feature, they determined the similarity of shapes by using topological relationship proposed by El-Mehalawi et al. (2003a, 2003b), which expresses the topological relationship of the surface of a product shape in CAD model. However, as long as the topological relationship is used, the similarity between the removal volume and the geometric properties of the machining case data cannot be recognized correctly as the product shape becomes more complicated. For example, when there are many closed pockets on a product model, the topological relationship of the product is too complicated to recognize closed pockets separately. Furthermore, in the previous method, it is difficult to clarify the difference among multiple removal volumes, which have similar shapes but different volumes or dimensions.

This study proposes a new method to recognize the similarity between the removal volume and the geometric properties of the machining case data according to the geometric features of Split Removal Volume (SRV), which is extracted from Total Removal Volume (TRV). SRV means the minimum removal volume, which cannot be split by its composed surface planes. The proposed method can apply to practical complicated product shape because the shape of SRV is simple even if the product shape becomes complicated. This study aims to realize the automatic NC program generation so as to reflect the experience and the know-how of skillful operators by reusing machining case data. This study will contribute to shorten time for arrangements in machining operation.

2. Extraction of removal volume for the recognition of the similarity

This study recognizes the similarity between the target removal volume and the machining case data by the geometric features of SRV extracted from TRV. In the extraction of SRV, the CAPP system, which is proposed by our research group (Nishida et al., 2017), is used. TRV is extracted from work material and product shape by Boolean operation as shown in Figure 1. In the extraction of SRV, TRV is firstly split by the suitable plane for machining. First, the major plane, which can split the TRV into more than or equal to 3 bodies, is detected and the TRV is split by this major plane as shown in Figure 2. Then, the SRV is split in a similar way until the major plane, which can split the SRV into more than or equal to 3 bodies does not exist.

Subsequently, SRV is split further by the planes, which is constitute the SRV and can split the SRV. When there is no plane which can split the SRV, the SRV of minimum unit can be extracted. By the detection of SRVs as described...
above, TRV can be split to simple shapes even if the product shape is complicated. After the extraction of the SRVs, the machining sequence is determined by the descending order of the number of open faces on each SRV. The open face means that the face contacts the atmosphere and is easy to approach for machining. The number of the open faces on the SRV is calculated from the remaining work material, which is updated by the progress of removing or machining each SRV. Figure 3 shows the example of the extraction of SRV and the machining sequence.

In the proposed CAPP system, SRV is detected from TRV split by the planes in order to determine removal volume and machining sequence geometrically. Although the simple shape like SRV of minimum unit is required to determine the machining sequence, it is difficult to generate the suitable tool paths from the extracted SRV as it is. For example, when TRV is extracted as shown in Figure 4(a), SRVs are extracted from the TRV split by the planes. When the tool paths are generated for each SRV as it is, the tool path generation is completed for each SRV as shown in Figure 4(b). The generated tool paths are not suitable for the machining operation. In order to improve the tool path generation, it will be better to generate tool paths for the large removal volume as possible. In this study, the SRV in the following order is integrated to remake the larger SRV, in which the tool approach surface becomes a convex polygon, as shown in Figure 4(c).

3. Storage and reference of machining case data
3.1 Similarity recognition of removal volume

This study proposes a new method to utilize the similarity of removal volume to select the most similar machining case data according to the properties of the extracted SRV.

In this study, the geometric similarity is recognized by the SRV extracted in the CAPP system as described above. The geometric shape of SRV is defined as following, because the SRV is so simple not to be split any more.

- Sphere
- Polyhedron
- Polygonal pyramid (Including the shape which bottom surface is circle)
- Polygonal prism (Including the shape which top and bottom surfaces are circle)

![Fig.3 Determination of machining sequence of the extracted SRV according to the number of open face of SRV](image-url)

(a) SRV extracted from TRV  
(b) Remaining SRV after removing the first SRV  
(c) Descending order of the number of open face

![Fig.4 Tool path generation to remove extracted SRV. SRV in the following order is integrated to remake the larger SRV, in which the tool approach surface becomes a convex polygon.](image-url)

(a) Extracted SRVs  
(b) Tool path generation  
(c) Improved tool path generation
In machining field, the geometric shape of SRV is generally limited to polygonal pyramids or polygonal prisms because the extracted SRV does not correspond to sphere or polyhedron. Furthermore, this study assumes that the tool approach surface is a flat plane.

This study defines the properties of the extracted SRV described as following for the similarity recognition.

1. Material of workpiece
2. Shape of tool approach surface
3. Aspect ratio and scale of tool approach surface
4. Machining depth
5. Volume
6. Type of machining feature

The type of machining features as shown in Figure 5 is a classification of features which are appeared after removing the SRV. The cutting conditions can be determined by considering the type of machining feature. When the shape and scale of SRV are the same, the cutting conditions can be modified suitably by recognizing the differences of the properties of the SRV.

In order to reuse the machining case data, the most similar machining case data is retrieved by excluding machining case data according to the differences of the properties of SRV. Figure 6 shows the flowchart to retrieve the most similar machining case data from a database.

First of all, all stored case data is read from the database. Then, the case data with the different material is excluded from the candidate case data. The cutting force is strongly depending on the material of workpiece. Therefore, the cutting conditions should be changed when the material of workpiece is different. Subsequently, the case data with the different shape of approaching surface is excluded from the candidate case data. It is used for the recognition of drilling or milling because the machining pattern is different between drilling and milling. It is also used for the recognition of machining feature (pocket or hole) because the machining pattern is different among the machining feature. Subsequently, the case data with the different aspect ratio and scale of tool approaching surface is excluded from the candidate case data. The machining is generally conducted from the same Z level region. Therefore, when the aspect ratio and scale of tool approach surface is the same, the cutting condition can be the same. Then, the allowance range of differences is defined so that the candidate case data remains as much as possible. The allowance range is initially set as 25% and decreasing gradually by 5%. Subsequently, the case data with the different machining depth and volume is excluded from the candidate case data. The axial depth of cut depends on the machining depth. The volume is partially used for the recognition of the solid shape. The machining depth and the volume also depends on the allowance range. Finally, the case data with the different type of machining feature is excluded from the candidate case data because it is possible to remain the case data, which has the same parameters other than the machining feature. In the exclusion of each property, the most similar machining case data is determined when one case data remains.

![Fig.5 Types of machining features considered in this study. Machining feature is recognized from the number of the open faces of the machining region and the shape of the tool approaching surface.](image-url)
3.2 Reference of machining case data

The cutting conditions, which are required for the automatic generation of NC programs, are defined as following.

- Process Type (such as drilling, milling, roughing, semi-finish, finish and so on)
- Tool ID (Including the specifications such as tool diameter, tool length, tool material and so on)
- Spindle speed
- Feed rate
- Radial depth of cut
- Axial depth of cut

Cutter location (CL) data to generate an NC program can be calculated automatically according to the cutting conditions and the removal volume shape. Especially, these cutting conditions stored in the machining case database are originally determined by the skillful operator, who knows the machining operation very well. In this study, because these cutting conditions are linked with the properties of SRVs, the cutting conditions determined from the most similar machining case data are reflecting the know-how of the skillful operators.

In practical machining operation, one SRV is machined by not only single process but also multi-process. For example, in the machining of closed pocket, rough machining by a square end mill with large diameter, and finish machining by a ball end mill with small diameter are performed. Therefore, multiple cutting conditions linked with the properties of each SRV enables to be stored for the practical tool path generation as shown in Figure 7.
3.3 NC program generation

An NC program for the machining operation can be generated automatically by our original CAM software, which is developed by using SolidWorks 2015 API and Visual Studio 2015 (C#). The software can calculate CL data according to the geometrical properties, such as the tool approach surface, of the extracted SRV and the cutting conditions determined from the machining case data.

4. Case study

A case study for 2.5D machining was conducted in order to validate the proposed method. In this case study, a new product model shown in Figure 8(a) is prepared. This model has a closed pocket, which has curved form bottom, an L-shape closed pocket and two through holes. Furthermore, 12 reference product models shown in Figure 8(b) are prepared in order to store the machining case data including cutting conditions linked with the properties of SRVs. The Models 1-3 have the blind holes with the different diameter and the same aspect ratio (Length / Depth). The Models 4-9 have the closed pockets with the different width, length and height. The Models 10-12 have the closed pockets, which have curved form bottom, with the different width. The size of each reference product model is shown in Figure 8(b).
In the developed system, cutting conditions are stored in the machining case data operated by the skillful operators, who knows machining operation very well, interactively when the system calculates the removal volume and the machining sequence. Figure 9 shows the input dialog to set cutting conditions. Multiple cutting conditions for both rough and finish machining linked with the properties of each SRV can be stored in the machining case data because an operator can select or set another process into the same removal volume. The proposed system is considered to store the know-how of skillful operators by setting cutting conditions interactively as described above.

The result of this case study is shown in Figure 10. Six SRVs were extracted from a new product model as shown in Figure 10(a). The cutting condition was determined for the integrated area of SRV3 and SRV4, because the approaching surface became a convex polygon by combining SRV3 with SRV4 as shown in Figure 10(b). In SRV1 and SRV2, the determined cutting conditions were confirmed to be the same cutting conditions stored in the most similar reference model Model2 shown in Figure 8(b). In the integrated area of SRV3 and SRV4, the determined cutting conditions were confirmed to be the same cutting conditions stored in the most similar reference model Model7 shown in Figure 8(b). In SRV5, the determined cutting conditions were also confirmed to be the same cutting conditions stored in the most similar reference model Model5 shown in Figure 8(b). Furthermore, in SRV6, the determined cutting conditions were also confirmed the same cutting conditions stored in the most similar reference model Model1 shown in Figure 8(b) for both rough machining and finish machining. The result of this case study shows that the proposed system can automatically determine cutting conditions by recognizing the most similar machining case data even many machining case data with the similar shape exist in database.

Figure 12(a) shows the result of the calculated tool paths based on the automatically determined cutting conditions. Figure 12(b) shows the product machined by the NC program generated by the proposed method. The result shows that the cutting experiment was performed successfully by the generated NC program.

The developed system finds out the most similar machining case data by the properties of the extracted SRVs from database to determine the suitable cutting conditions. It is similar to the way done by the skillful operators in their CAM operation. The skillful operators find out the most similar machining case data according to their experience or know-how to determine the suitable cutting conditions. And the most similar machining case data has implicit experience or know-how to satisfy the required machining accuracy, machining time and the performance of tool. Therefore the developed system realizes to automatize NC program generation to satisfy the required machining accuracy, machining time and the performance of tool as same as the skillful operators. Additional machining case data stored using this system will improve the quality to decide the suitable cutting conditions. At this point, the developed system has some limitation that the tool approach surface needs to be a flat plane in order to recognize the shape and the scale of the tool approach surface. These limitations will be solved in our future work.
Fig. 10 Extraction of SRVs and integration of SRV3 and SRV4 in case study. SRV3 and SRV4 were integrated because the approaching surface became a convex polygon when combining SRV3 with SRV4.

Fig. 11 The most similar reference product model with the extracted SRVs. The cutting conditions linked with the reference product model are used.

Fig. 12 Calculated tool paths and Machined product. The cutting conditions can be determined and the NC program can be generated automatically by the proposed method to realize machining operation.

5. Conclusion

A new method to automatically determine cutting conditions for NC program generation by utilizing the similarity of the geometric properties of the removal volume is proposed. Remarkable conclusions are summarized as follows.

1. It becomes possible to retrieve the suitable cutting conditions from the machining case data according to the similarity of the removal volume.
2. The cutting conditions stored in the machining case data are originally determined by the skillful operator. The know-how of skillful operators can be referred from the retrieved cutting conditions.

3. In the case study, an NC program was generated successfully based on the suitable cutting conditions retrieved from the machining case data. The machining operation was performed without any trouble by the generated NC program in the cutting experiment.

Although there is the limitation that the tool approach surface needs to be a flat plane, the automation of NC program generation considering the know-how of skillful operators can be realized in this study. This results strongly contributes to shorten the machining process lead time.

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