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Automated Process Planning System for End Milling Operation Constrained by Geometric Dimensioning and Tolerancing (GD&T)

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To realize autonomous machining, it is necessary to focus on machining tools and also on the automation of process planning in the preparation stage. This study proposes a process planning system that automatically defines the machining region and determines the machining sequence. Although previous studies have explored computer-aided process planning, only a few have considered geometric tolerances. Geometric tolerances are indicated on product drawings to eliminate their ambiguity and manage machining quality. Geometric dimensioning and tolerancing (GD&T) is a geometric tolerance standard applied to a three-dimensional computer-aided design (3D CAD) model and are expected to be used for the digitization of manufacturing. Therefore, this study developed an automated process planning system by using GD&T as a sequencing constraint. In the proposed system, the machining sequence is automatically determined by the geometrical constraints, which indicate whether the tool can approach, and GD&T, which indicates the geometric tolerance and datum in a 3D CAD model. A case study validated the proposed method of automated process planning constrained by GD&T. The result shows that the proposed system can automatically determine the machining sequence according to the geometric tolerance in a 3D CAD model.

Keywords: geometric dimensioning and tolerancing (GD&T), geometric tolerance, automation, process planning, NC program

1. Introduction

Numerical control (NC) machine tools are widely used in industrial production. In particular, end milling is used in factories as it is indispensable for machining complex parts. As NC programming is essential for machining using NC machine tools, computer-aided design (CAD) and computer-aided manufacturing (CAM), which support the preparation of a NC program, have been rapidly developed. However, existing software cannot completely realize the automated generation of a NC program because operators have to manually determine the machining region, sequence, and conditions and input them into the software. In other words, it is necessary to prepare product-specific NC programs for automated machining with NC machine tools. As the number of products increases and their life span reduces, the time required for generating NC programs becomes enormous. Therefore, to shorten the operation time, computer-aided process planning (CAPP) is required to support the generation of a NC program by a computer. Several previous studies have proposed CAPP systems. These have generally proposed a method for recognizing machining features [1] that characterize the machining process. Two methods that have been proposed for machining feature recognition are recognizing a target shape [2–6] and recognizing a removal volume [7–16]. In addition, previous CAPP studies have determined the machining sequence based on the geometrical constraints imposed by the tool approach. However, a multitude of machining sequences needs to be calculated as candidates when using only the geometrical constraints of the tool approach. The CAPP system should determine at least one machining sequence from the calculated candidates. To accomplish this, methods that add additional constraints have been proposed, such as minimizing the tool path distance [8] and the number of tool changes [16]. A machining sequence can be effectively chosen by adding another constraint according to the machining situation and purpose. The present study proposes a method for machining sequence determination by adding a geometric dimensioning and tolerancing (GD&T) constraint. GD&T is a system promoted by the American Society of Mechanical Engineers (ASME) and established as ASME Y14.41, *Digital Product Definition Data Practices*, and ASME Y14.5M, *Dimensioning and Tolerancing*. Previous researches using GD&T [17–20] mainly deal with product design, assembly, and measuring. Few previous researches use GD&T for the automation of process planning. Generally, geometric tolerance in a product drawing eliminates ambiguity and manages the machining quality when the product is designed. In the proposed method, it is not necessary for the automated process planning to provide additional informa-

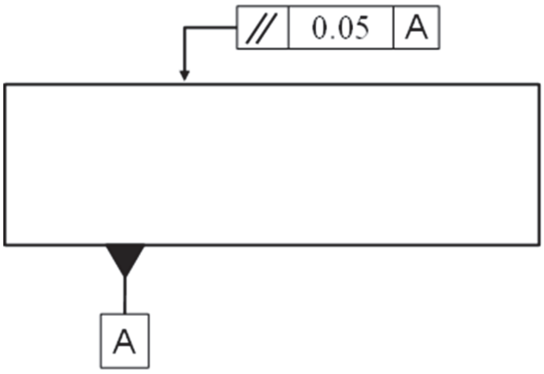


Fig. 1. Notation of geometric tolerance and datum.

tion because it uses only GD&T information indicated in a 3D CAD model, which is set when the product is designed. Furthermore, the machining sequence obtained by the proposed method has been considered effective in various studies such as in automatically conducting on-machine measurements during machining [21]. The proposed machining sequence can be applied when conducting machining and measurement in turns, instead of having to conduct measurement after machining all regions.

2. Automated Process Planning System Constrained by GD&T

2.1. Properties of Geometric Tolerance

Industrial products have become extremely sophisticated and refined. Therefore, every part of a product requires high accuracy and compatibility with other components. Geometric tolerance focuses on meeting these demands. Generally, workpieces have geometrical features such as planes and lines. As it is impossible to obtain a geometrically perfect state for these shapes, an allowable deviation must be determined in advance and indicated in the drawing. The allowable deviation, with respect to each feature, is called the geometric tolerance. The notation of geometric tolerance and its reference datum are given in **Fig. 1**. It includes geometric tolerance symbols, tolerances, and a datum (black triangle marked as “A”) as references for the dimensions to be measured. Typical geometric characteristic symbols are listed in **Table 1**. There are two types of features, namely (1) individual features, which are not related to a datum (indication of a reference datum is unnecessary), and (2) related features, which are related to a datum (indication of a reference datum is necessary). The type of tolerance that is not related to a datum is classified as a form. The form does not depend on the machining sequence but rather depends on the machining conditions and accuracy of the machining tool. Therefore, in this study, where the objective is to automatically determine the machining sequence, a tolerance that is not related to a datum is not considered. Thus, we consider only the tolerances that are related to a datum.

Table 1. Geometric characteristic symbols.

(ASME Y14.5M-1994)

Type of feature	Type of tolerance	Characteristic	Symbol
Individual features	Form	Straightness	⏤
		Flatness	▱
		Circularity (roundness)	○
		Cylindricity	⌭
Individual or related features	Profile	Profile of a line	⌒
		Profile of a surface	⌓
Related features	Orientation	Angularity	∠
		Perpendicularity	⊥
		Parallelism	//
	Location	Position	⌖
		Concentricity	◎
		Symmetry	⌯
	Runout	Circular runout	↗
		Total runout	⌰

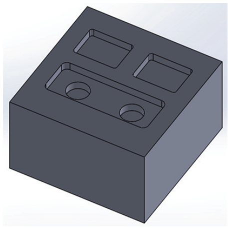
2.2. Machining Removal Volume and Geometrical Constraints

Our previous study proposed a method for extracting the total removal volume (TRV) from the work material and product using Boolean operators and split removal volume (SRV) obtained by dividing the TRV into regions suitable for actual machining [15]. In machining, as the tool can approach only the surface where the work material is in contact with the atmosphere, geometric constraints exist for the SRV machining sequence. Our previous study proposed a method for association chart calculation, where the geometric constraints were expressed using a hierarchical structure [16].

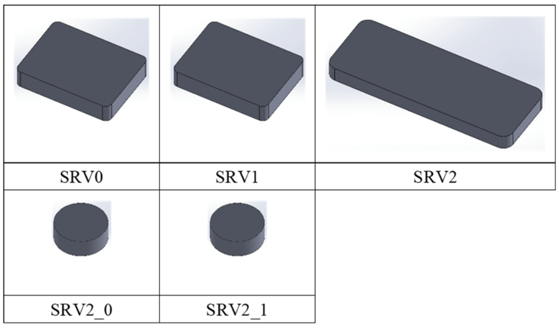
Figures 2(a) and **(b)** show the product shape and extracted SRVs, respectively. The SRVs initially machined from the workpiece are SRV0, SRV1, and SRV2, which are in contact with the atmosphere. SRV2_0 and SRV2_1 can be machined only after SRV2 has been machined. The association chart, shown in **Fig. 2(c)**, is obtained by considering the geometric constraints (i.e., whether the tool can approach the SRV). By using the method proposed in the previous study, it is possible to limit the candidates for machining sequence according to the geometrical constraints by simply inputting the 3D CAD data into the workpiece and product models.

2.3. Determination of Machining Sequence Constrained by GD&T

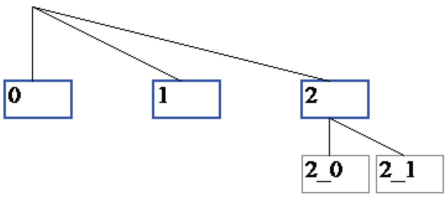
The study proposes a method to automatically determine the machining sequence by adding the geometric



(a) Product model



(b) Extracted split removal volumes (SRVs)



(c) Generated association chart

Fig. 2. Generation of the association chart from the product model and the extracted split removal volumes (SRVs).

tolerance indicated in a 3D CAD model as a constraint. The machining sequence can be automatically determined based on the following GD&T rules.

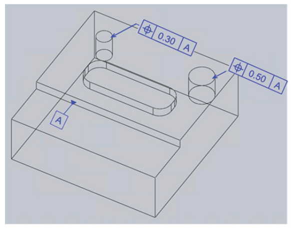
Rule 1. SRVs, where neither a datum nor geometric tolerance is indicated, are machined as top priority.

Rule 2. SRVs, where a datum is indicated and referenced as a geometric tolerance by another SRV, are machined with priority.

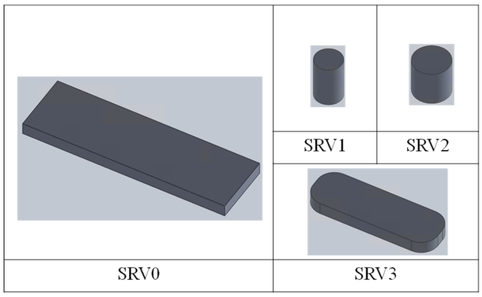
Rule 3. SRVs, where a geometric tolerance with a larger value is indicated, are machined with priority.

In rule 1, normally, SRVs where neither a datum nor a geometric tolerance is indicated can be machined in any order. However, according to the geometrical constraints described in Section 2.2, the tool approach for other SRVs is possible by first machining the SRVs based on priority. To avoid excessive candidate limitations for the machining sequence, SRVs where neither a datum nor a geometric tolerance is indicated are machined with top priority.

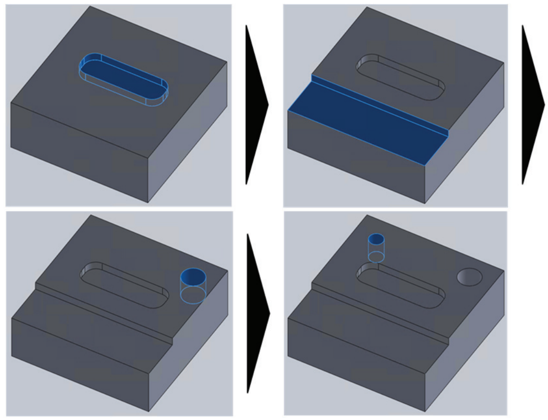
In rule 2, the indicated geometric tolerance always refers to a datum because the present study considers only datum-related tolerances. Therefore, SRVs where the referenced datum is indicated is machined with priority. A datum must be machined with priority to measure the geometric tolerance region when verifying whether



(a) Product model



(b) Extracted SRVs



(c) Determined machining sequence

Fig. 3. Example of the machining sequence determination constrained by GD&T.

the machined shape satisfies the specified geometric tolerance.

In rule 3, an SRV with a small geometric tolerance must be machined carefully. In the proposed system, the SRV that needs the most accuracy, such as the one with the smallest geometrical tolerance, is machined last, owing to the influence of workpiece deformation when other regions are machined. However, this condition can be altered because it is assumed that machining that needs accuracy has priority, depending on the machining environment and the target product shape.

As the purpose of this study is to automatically determine the machining sequence for the SRVs, roughing and finishing operations are not considered separately, but assumed to be continuous for each SRV.

According to the rules described above, the machining sequence for a 3D CAD model where the datum and geometric tolerance are indicated as shown in **Fig. 3**, for example, can be determined as follows.

The extracted SRVs are SRV0, SRV1, SRV2, and

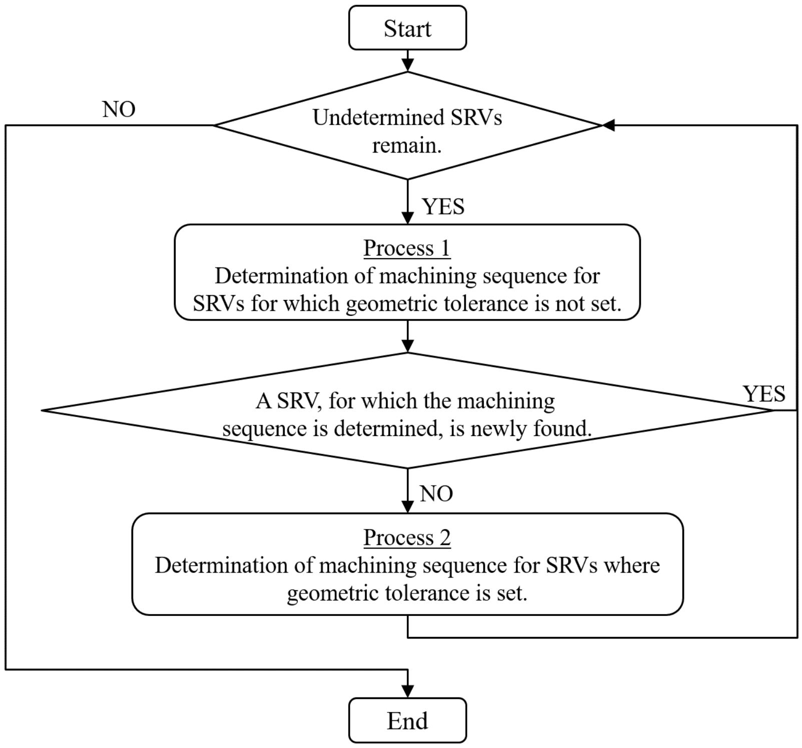


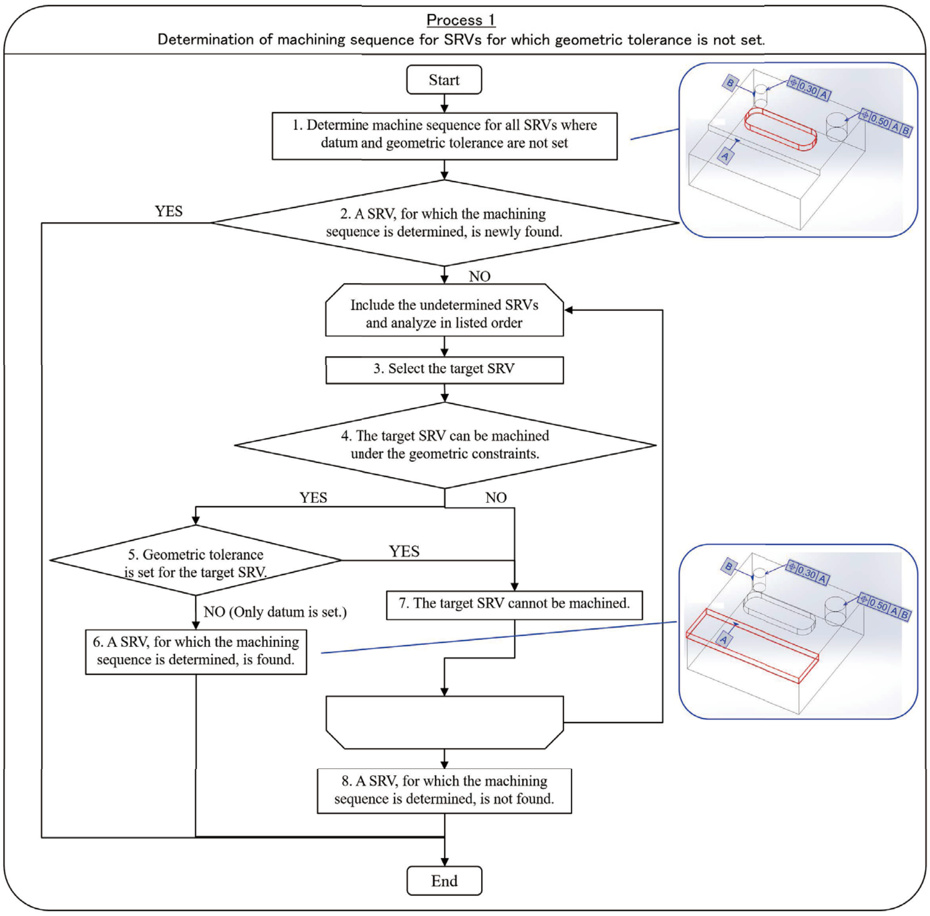
Fig. 4. Flowchart for the main process for the determination of the machining sequence constrained by GD&T and geometric constraints.

SRV3. According to rule 1, SRV3, which has neither a datum nor a geometric tolerance, is machined first. Subsequently, according to rule 2, SRV0, for which a datum is referenced by the geometrical tolerance indicated in SRV1 and SRV2, is machined with priority. Although the remaining SRV1 and SRV2 have a geometric tolerance, according to rule 3, SRV2, which has a larger geometric tolerance value, is machined with priority. Thus, SRV1 is machined last.

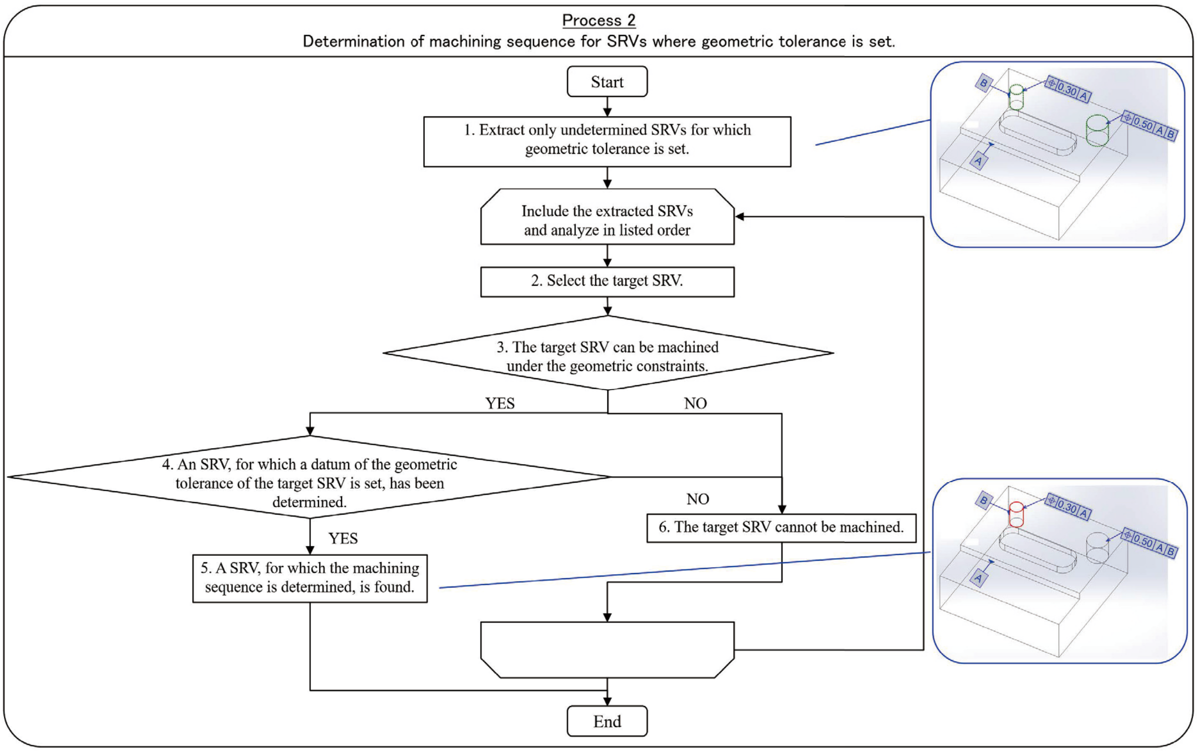
In this example, the product shape is simple enough to ignore the geometrical constraints described in Section 2.2. However, when the 3D CAD model is complicated, the machining sequence cannot be determined by just applying the rules for GD&T owing to the geometrical constraints. To apply GD&T-constrained rules, the machining sequence is determined based on the flowcharts shown in **Figs. 4** and **5**. **Fig. 4** shows the flowchart for the main process, and **Fig. 5** shows the flowchart for the two sub-processes. The application of the flowcharts is explained below.

First, all SRVs that can be machined according to the geometrical constraints of the association chart, and for which neither a datum nor a geometric tolerance is indicated, are machined (Process 1, Step 1). When SRVs to be machined are under this condition, the number of machining sequence candidates is the factorial of the number of SRVs. It is assumed that the machining sequence can be arbitrary because the study focuses on GD&T. When one or more SRVs to be machined are under this condition, the CAPP system exits Process 1 and returns to the main process. When there are no SRVs to be machined under this condition, the CAPP system searches for SRVs that can be machined according to the geometrical constraints for tool approach, and where only a datum is indicated. When such an SRV is found, the CAPP system exits Process 1 and returns to the main process (Process 1, Steps 3–6). This prevents excessive limitation of the number of machining sequence candidates because the tool approach of SRV at the lower level of the association chart is enabled after machining SRVs at the upper level. However, when there are no SRVs to be machined under Process 1, the CAPP system exits Process 1 and returns to the main process (Process 1, Steps 7–8).

Subsequently, when there are no SRVs to be machined under Process 1, the CAPP system uses Process 2 to search for SRVs that can be machined according to the geometrical constraints of the association chart and for which a geometric tolerance is indicated. Among the remaining SRVs, the ones extracted are those for which the geometric tolerance is indicated (Process 2, Step 1). Among these, the system searches for SRVs that can be machined according to the geometrical constraints of the association chart, where the SRV referencing the datum for geometric tolerance has already been machined. When there is an SRV to be machined under this condition, the CAPP system exits Process 2 and returns to the main process (Process 2, Steps 2–5). As in Process 1, this prevents excessive limitation of the number of machining sequence candidates. In Process 2, there must always be an SRV to be machined. When there are no SRVs to be machined,

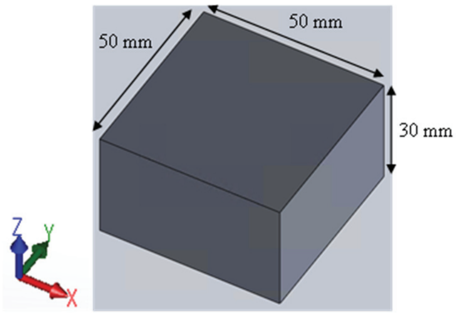


(a) Sub-process for SRVs where the geometric tolerance is not set (Process 1)

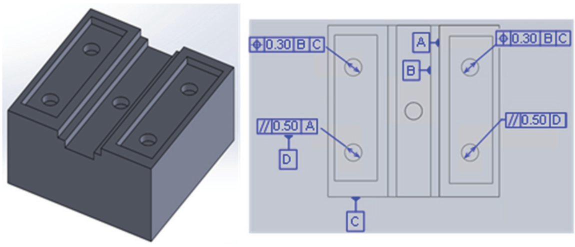


(b) Sub-process for SRVs where the geometric tolerance is set (Process 2)

Fig. 5. Flowchart for the determination of the machining sequence.



(a) Work material



(b) Product and GD&T

Fig. 6. Models for case study.

the 3D CAD model needs to be modified to conform to the relationship between the indicated datum and geometric tolerance.

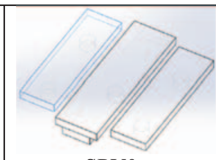
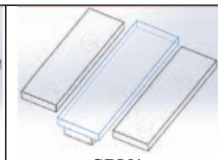
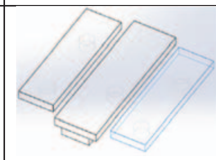
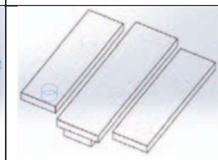
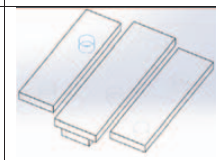
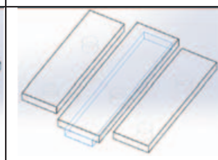
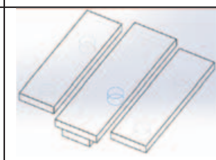
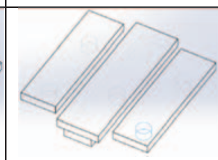
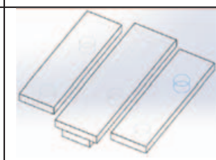
By repeating the above steps, it is possible to determine the machining sequence for all extracted SRVs. The study used SolidWorks 2018 for the analysis of the 3D CAD model. GD&T information indicated in the 3D CAD model was obtained by using the SolidWorks API (GetSpecificAnnotation function). The study developed the CAPP system using Visual Studio 2015 (C#) and analyzed the NC program with the surface of the 3D CAD model associated with the obtained datum and geometric tolerance related to the same surface of the extracted SRV.

3. Case Study

3.1. Properties of Geometric Tolerance

To validate the effectiveness of the proposed CAPP system constrained by GD&T, a case study was conducted. The work material shown in **Fig. 6(a)** and the product model shown in **Fig. 6(b)** were prepared for the study. GD&T information was indicated in the product 3D CAD model, as shown in **Fig. 6(b)**. Nine SRVs were extracted from CAD models of the work material and the product, as shown in **Table 2**. **Table 2** also shows the datum and geometric tolerance for each SRV. The association chart for the SRVs, which shows the geometric constraints, is presented in **Fig. 7**. In the association chart, SRV0, SRV1, and SRV2 are at the top and can, thus, be machined using the initial work material shape. Furthermore, at the lower level of the association chart, the subordination relationship among the SRVs can be obtained by considering the geometric constraints. For example, SRV1_0 can be machined after SRV1 has been machined. Furthermore, SRV0_0 and SRV0_1 can be machined after SRV0 has been machined, which is at a higher level in the association chart than SRV0_0 and SRV0_1.

Table 2. SRVs extracted from the TRV, and datum and geometric tolerance for each SRV.

SRV	 SRV0	 SRV1
Datum	-	A
Geometric tolerance	-	-
SRV	 SRV2	 SRV0_0
Datum	-	D
Geometric tolerance	-	// 0.50 A
SRV	 SRV0_1	 SRV1_0
Datum	-	B
Geometric tolerance	⌖ 0.30 B C	-
SRV	 SRV1_0_0	 SRV2_0
Datum	-	-
Geometric tolerance	-	// 0.50 D
SRV	 SRV0_3_1	
Datum	-	
Geometric tolerance	⌖ 0.30 B C	

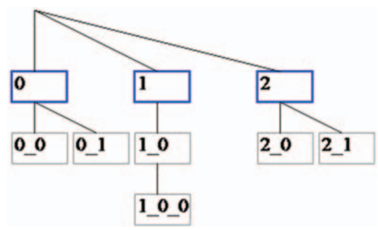


Fig. 7. Association chart showing the dependence hierarchy for all SRVs, as generated by the CAPP system.

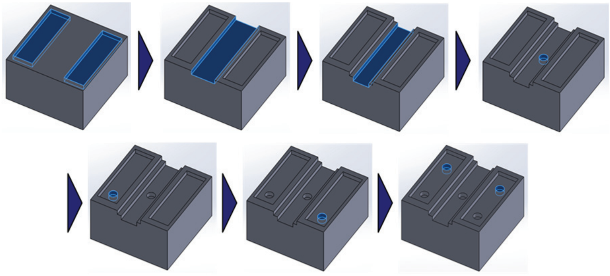
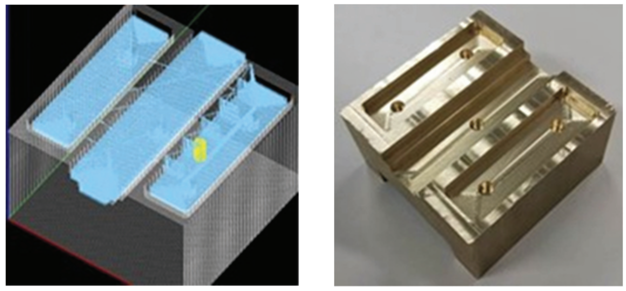


Fig. 8. Machining sequence calculated using the proposed CAPP system.



(a) Calculated tool paths (b) Machined product

Fig. 9. Result of cutting experiment.

The result of the machining sequence determined according to the proposed method constrained by GD&T is shown in **Fig. 8**. It can be seen that SRV0 and SRV2 are machined first. Although SRV0, SRV1, and SRV2 are at the top of the association chart and can be machined from the initial work material shape, SRV0 and SRV2 were machined first because neither a datum nor a geometric tolerance is indicated for these. The machining sequence of SRV0 and SRV2 can be arbitrarily changed. Next, SRV1 was machined.

Although SRV1, SRV0_0, SRV0_1, SRV2_0, and SRV2_1 can be machined after SRV0 and SRV2 have been machined, SRV1 was machined with priority because a datum was indicated for SRV1. Subsequently, SRV1_0 was machined. Although there are pending SRVs to be machined after SRV1 has been machined, SRV1_0 gets priority because the geometric tolerance was indicated for all the remaining SRVs, except SRV1_0. Subsequently, SRV1_0_0 was machined. Similar to SRV1_0, SRV1_0_0 was machined with priority because the geometric tolerance was indicated for all the remaining SRVs, except SRV1_0_0. Next, SRV0_0 was machined. Among the tolerance values for the remaining SRVs, the values for SRV0_0 and SRV2_0 were larger than those of SRV0_1 and SRV2_1. The geometric tolerance indicated for SRV2_0 was referenced to the datum indicated for SRV0_0. Therefore, SRV0_0 had to be machined prior to SRV2_0. Subsequently, SRV2_0 was machined because the tolerance value for SRV2_0 was the largest of the remaining SRVs. Finally, SRV0_1 and SRV2_1 were machined. The machining sequence of SRV0_1 and SRV2_1 can be arbitrarily changed because they have the same tolerance value. In these models, the number of possible machining sequence candidates is 362,880 (9!) with no consideration as the number of extracted SRVs is 9. When considering only the geometric constraints expressed in a hierarchical structure [16], the number of machining sequence candidates is 6,720 (${}_9C_3 \times {}_6C_3 \times 2 \times {}_3C_3 \times 2$). In contrast, the number of machining sequence candidates is 4 using the proposed method, which does not need additional information other than the current design information.

Finally, a machining experiment was conducted by generating a tool path and NC program, as shown in **Fig. 9(a)**, where the material used was brass (C3604) and the cutting conditions included a tool diameter of 2.5 mm and radial and axial depths of cut as 0.5 mm, according to the determined machining sequence. BESTOWS Process Planning (BESTOWS Co., Ltd.) was used to generate the NC program. **Fig. 9(b)** shows the workpiece after machining. This case study verified that the proposed method could determine an executable machining sequence without machining difficulties.

According to the results of the case study, the machining sequence can be automatically determined based on the geometrical constraints of the association chart and by obtaining GD&T information indicated in a 3D CAD model.

4. Conclusions

A CAPP system was developed that could automatically determine the machining sequence by using the GD&T indicated in a 3D CAD model, and the geometrical constraints according to the tool approach. The geometric tolerance is indicated in the product drawing to eliminate ambiguity and manage the machining quality. GD&T is increasingly applied in 3D CAD models and is expected to be used for digital manufacturing. This study aimed to automatically determine the machining sequence constrained by GD&T without providing additional information. To validate the proposed system, a case study was conducted. The conclusions can be summarized as follows.

(1) The study proposed the rules related to GD&T for machining sequence determination.

(2) The system incorporating the GD&T-related rules can automatically determine the machining sequence according to the indicated GD&T and the geometrical constraints. However, numerous machining sequences are calculated as candidates with only the geometrical constraints based on tool approach.

The developed CAPP system can automatically define the machining region and determine the machining sequence, which were earlier performed by skilled operators. This system strongly contributes to shortening the machining process lead time.

Acknowledgements

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