Sequence planning of on-machine measurement and re-machining

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Abstract
In order to realize autonomous machining, it is necessary not only to automate the preparation tasks for machining but also to verify the machining results during the process. Therefore, this study realized the automation of planning for on-machine measurement, where measurement is conducted at the necessary time during the machining process based on process planning. Furthermore, when a machining abnormality is detected based on the measurement results, the proposed system automatically judges whether to stop machining or to re-machine the affected region. In the proposed system, measurement is conducted after the machining of a region that has an influence on the next machining process according to the association chart, which shows the subordination relationships of the geometrical constraints among removal volumes. If measurements indicate excess cutting, the system immediately stops machining because it is impossible for the workpiece to be modified. If measurements indicate incomplete cutting, the system re-machines the affected region and continues the machining process by recursively applying the NC program for the target removal volume. A case study was conducted in order to validate the proposed method of automated planning of on-machine measurement and re-machining. The result showed that the proposed system can automatically determine whether to stop or continue machining according to the measurement results.

Keywords: On-machine measurement, Re-machining, Automation, Process planning, NC program

1. Introduction

Numerical control (NC) machine tools are widely used in industrial production. When the target product machined by a NC machine tool is large and each product must be manufactured individually, it is important to manage the quality of the machining process. To improve machining accuracy and production efficiency, a measurement method that utilizes sensors attached to machine tools has been proposed (Kakino et al.,1993; Kohno, 1996). Previous studies have used measurement before and after machining and applied compensation to increase machining accuracy; however, the measurement sensors were expensive, measurement accuracy was relatively poor, and high-precision measurements were time-consuming. Recently, improvements in sensors have made it possible to realize measurement on machine tools, called on-machine measurement (Takaya, 2014). On-machine measurement can reduce the setup time and positioning error for reloading a workpiece, because the workpiece can be measured on the machine tools (i.e., without loading and unloading). There are several approaches to on-machine measurement, including non-contact measurements using a laser displacement sensor or imaging equipment and contact measurements using a touch probe. A touch probe is barely affected by the cutting oil and coolant, and can be relatively easily installed on a machine tool (it is directly attached to the spindle). However, the measurement accuracy depends on the positioning accuracy of the machine tools because the touch probe is attached to the spindle (Ihara and Ohtsuka, 2009; Ueno, 2009). In addition to the positioning accuracy of the machine tool, tool wear is a factor that affects machining error, and thus on-machine measurement with a touch probe is useful for detecting machining error. To conduct measurements with a touch probe,
it is necessary to generate an NC program. In general, operators have to specify the target shape and create a measurement plan, involving factors such as the measurement order and the position of measurement points, so as to specify the probe path. Several studies have been conducted on touch probe path generation for on-machine measurement (Cho et al., 2004; Jeon et al., 2016; Lee et al., 2004). However, in these studies, the probe path was generated based only on the final product shape after all machining processes by NC machine tools had completed. However, for process control, measurement of a region that affects machining in the next process should be conducted during the machining process (i.e., after the machining of that region). Furthermore, when some machining abnormality that affects product quality occurs during the machining process, the abnormality should be detected and measured at an early stage to avoid unnecessary machining. Our research group previously proposed an automated tool path generation method for the realization of autonomous machining with NC machine tools (Nishida et al., 2017, 2018a, 2018b, 2018c). However, in order to realize autonomous machining, it is necessary not only to automate the preparation tasks for machining but also to verify the machining results during the process. Therefore, this study aims to realize the automation of planning for on-machine measurement, where measurement is conducted at the necessary time during the machining process based on process planning. Furthermore, when a machining abnormality is detected based on the measurement results, the proposed system automatically judges whether to stop machining or to re-machine the affected region.

2. Sequence planning of on-machine measurement using association chart

Operators can determine the target shape for measurement and the measurement region. For example, operators can recognize the difference between a slot and a hole and can find where these regions are located. However, it is necessary for the computer to understand the region to be measured and automatically determine the position of the measurement point according to the properties of the machining region. Our research group has proposed an automated measurement point determination method based on the volume removed from the product and the material model. In our previous study (Murase et al., 2018), the measurement points were automatically determined by defining them for each machining feature (Sugimura, 2006) classified from the geometrical properties of the removed material.

In the determination of the measurement points, the machining feature is classified to two groups. First group includes through pocket, through hole, closed pocket and blind hole, which have the open face only in the tool approach direction. Second group includes step, open slot, open pocket and closed slot, which have the additional open face besides the tool approach direction.

In the first group, the surface of the workpiece attaches on the removal volume in the X axis direction and the Y axis direction. Therefore, the measurement points for the length of X axis and Y axis are defined as the points deviated in the Z axis negative direction by \( r \) mm (\( r \) is the diameter of the tip sphere of the touch probe) from the edge of the removal volume as shown in Fig. 1. The measurement points for the length of Z axis are defined as the point located on the surface of the workpiece (deviated in the X axis negative direction by \( r \) mm (\( r \) is the diameter of the tip sphere of the touch probe) from the edge of the X axis of the removal volume) and the point located on the bottom of the removal volume as shown in Fig. 2.

![Fig. 1 Determination of measurement point for the length of X axis and Y axis](image-url)
In the second group, the open face, a normal vector of which is parallel to the X axis or Y axis, exists in the removal volume. Because the measurement point cannot be defined on the open face, it is necessary to define the measurement point on the surface of the workpiece. The measurement points for the length of X axis or Y axis are defined as the point located on the surface of the workpiece and deviated in the Z axis negative direction by \( r \) mm (\( r \) is the diameter of the tip sphere of the touch probe) from the bottom of the open face as shown in Fig. 3. In the second group, the direction of a normal vector of the open face is important. In the case shown in Fig. 3(a), the measurement point as mentioned above locates in the X axis positive direction. On the other hand, in the case shown in Fig. 3(b), the measurement point as mentioned above locates in the Y axis negative direction. The measurement points for the length of Z axis are defined in the same way as the first group.

As mentioned above, the length of X axis, Y axis and Z axis of the removal volume can be measured for each machining feature.

In our previous research (Murase et al., 2018), measurements were conducted at all measurement points after all machining processes had finished. However, measurements can be used not only for managing processing quality after machining but also for judging whether to continue to the next process during machining, as on-machine measurement eliminates the setup time required for reinstallation and the positioning error caused by reattachment. Therefore, when some machining abnormality occurs, it can be automatically detected in an early stage and the affected region can be automatically re-machined, so reducing the number of defective products. The present study proposes a method for automated measurement planning, in which the measurement is conducted after the machining of a region that affects machining in the next process in order to realize an autonomous manufacturing. This latter region cannot be approached by the tool before the former region is machined.
Our previous study proposed a method for extracting the total removal volume (TRV) from the work material and product using a boolean operation and extracting the split removal volume (SRV), which is obtained by dividing the TRV into regions suitable for actual machining (Nishida et al., 2017). In machining, since the tool can approach only the surface where the work material is in contact with the atmosphere, geometric constraints exist for the machining sequence for the SRV. Our previous study proposed a method for calculating the association chart, in which the geometric constraints are expressed in a hierarchical structure (Nishida and Shirase, 2018c). For example, Fig. 4(a) shows the product shape and Fig. 4(b) shows the extracted SRVs. The SRVs that can be 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 after SRV2 has been machined. The association chart, shown in Fig. 4(c), can be obtained by considering the geometric constraints (i.e., whether the tool can approach the SRV).

The association chart is generated as follows. First, SRVs for which the tool approach direction is normal to their surfaces and are in contact with the atmosphere are identified. Since the identified SRVs can be machined, they are at the top of the association chart. For the product shape shown in Fig. 4(a), when the tool approach direction is along the positive Z axis, SRV0, SRV1, and SRV2 are at the top of the association chart, as shown in Fig. 4(c). Subsequently, since the other SRVs can be machined after higher-level SRVs have been machined, the SRV is detected. Then, the subordination relationship of the association chart is determined by confirming whether unmachined SRVs whose surfaces are in contact with the atmosphere exist after higher-level SRVs have been machined one by one. For example, when SRV0 is machined, as shown in Fig. 5(b), no additional SRVs whose surfaces are in contact with the atmosphere are extracted. Therefore, no SRVs have a subordinate relationship to SRV0. Similarly, when SRV1 is machined, as shown in Fig. 5(c), no additional SRVs whose surfaces are in contact with the atmosphere are extracted. Therefore, no SRVs have a subordinate relationship to SRV1. In contrast, when SRV2 is machined, as shown in Fig. 5(d), SRV2_0 and SRV2_1, whose surfaces are in contact with the atmosphere, are additionally extracted. Therefore, there is subordination relationship between SRV2 at a higher level and SRV2_0 and SRV2_1 at a lower level. The association chart can be completed by examining the subordinate relationships among all SRVs.
(a) Diagram of SRVs that can be removed from the initial work material. Diagrams showing that no additional SRVs can be removed after machining

(b) SRV0

(c) SRV1

(d) Diagram showing that additional SRVs that can be removed after the machining of SRV2

Fig. 5 Evaluation of hierarchy dependency among SRVs for generating an association chart. The hierarchy dependency can be identified from the existence of a new open face in the tool approach direction.

The association chart clarifies the dependencies in the machining process. The machining of an SRV that has subordinate SRVs greatly influences the machining of the lower-level SRVs. Machining abnormalities can be detected at an early stage by conducting on-machine measurements immediately after the machining of SRVs that have subordinate SRVs. The measurement sequence can be determined from the machining sequence and the association chart, which are obtained in process planning (Nishida and Shirase, 2018c). For example, when the product shown in Fig. 5 is machined and the machining sequence obtained in process planning is SRV2→SRV0→SRV1→SRV2_0→SRV2_1, the association chart indicates that SRV2 has a great influence on SRV2_0 and SRV2_1. Therefore, the measurement sequence for SRV2 can be determined immediately after SRV2 has been machined. If other SRVs are to be machined using the same tool before the measurement, they are machined before the measurement to reduce the number of tool changes. In this example, if the same tool is used for machining SRV0, SRV1, and SRV2, the measurement of SRV2 is conducted after SRV0, SRV1, and SRV2 have been machined. If different tools are used for machining SRV0, SRV1, and SRV2, the measurement of SRV2 is conducted before SRV0 and SRV1 are machined.

3. Re-machining based on measurement results

When a machining abnormality is detected based on the results of on-machine measurement, it is necessary to judge whether to stop the machining process or to re-machine the affected region. If the measurement indicates excess cutting, re-machining cannot be conducted and the machining process is stopped. On the other hand, if it indicates incomplete cutting, it is possible to re-machine the target region. In the automated process planning system proposed by our research group (Nishida and Shirase, 2018b), a tool path is generated for each SRV. Therefore, re-machining can be conducted by loading only the same NC program of the target SRV recursively. Because it is difficult to precisely detect the region of incomplete cutting, this study re-uses the same NC program of target SRV for re-machining. The tool should be changed before re-machining because the incomplete cutting was caused by a worn or chipped tool. A flow chart of the proposed re-machining process based on measurement results is shown in Fig. 6. First, the machining of the SRV is conducted (Step 1). On-machine measurement is conducted after machining (Step 2). If the on-machine
measurement is within the tolerance limits (i.e., no machining abnormality has been detected), the machining of the next SRV is conducted (Step 3). On the other hand, if the on-machine measurement is outside the tolerance limits, it is determined whether re-machining can be performed. If the measurement indicates excess cutting, the machining process is stopped since re-machining cannot be conducted (Step 4). If it indicates incomplete cutting, re-machining is conducted after a tool change (Step 5). As described above, it is possible to detect defective products at an early stage without machining the next process while remaining machining abnormalities. Furthermore, wasteful machining is reduced by stopping the machining process or re-machining.

4. Case Study

In order to validate the effectiveness of the proposed method, a case study was conducted. In this case study, the work material shown in Fig. 7 (a) and the product model shown in Fig. 7 (b) were prepared. Two cases, namely one with excess cutting and one with incomplete cutting, were considered. Since in practice such errors rarely occur, to generate them, the wrong tool was intentionally used. For the excess and incomplete cutting cases, the diameter of the tool was 2 mm larger and smaller than that of the proper tool, respectively. The results of the case study are described below.

4.1 Validation of measurement planning

Five SRVs were extracted from computer-aided design (CAD) models of the work material and the product, as shown in Table 1. The association chart of the SRVs, which shows the geometric constraints, was obtained as shown in Fig. 8. In the association chart, SRV0 and SRV2 are at the top and can thus be machined from the initial work material shape. Furthermore, at the lower level of the association chart, the subordination relationship among SRVs can be obtained by considering the geometric constraints. For example, SRV1 can be machined after SRV0 has been machined. Furthermore, SRV3 and SRV4 can be machined after SRV1 has been machined, which is at a higher level in the association chart than SRV3 and SRV4. In this case study, machining was conducted using a machining sequence obtained from the association chart: SRV0→SRV1→SRV2→SRV3→SRV4. Furthermore, the tool to be used for each SRV was determined in advance. Table 2 shows information on the cutting tool, the workpiece material, and the cutting conditions.
Table 1  SRVs extracted from the TRV obtained from CAD model of work material and product

|   |   |   |
|---|---|---|
| (a) SRV0 | (b) SRV1 | (c) SRV2 |
| (d) SRV3 | (e) SRV4 |   |

Fig. 8  Association chart generated for case study.
Table 2 Tool used for each SRV and cutting conditions for case study

| Cutting tool | Tool type | Square end mill |
|--------------|-----------|-----------------|
| Workpiece    | Material  | FC250           |
| Cutting conditions | Axial depth of cut | 1.0 mm     |
|               | Radial depth of cut | 2.0 mm     |
|               | Spindle speed     | 5000 min⁻¹   |
|               | Feed rate         | 600 mm/min   |

Fig. 9  Machining sequence and measurement planning obtained using the proposed method.

First, the proposed measurement planning was verified. The results of the machining and measurement sequence are shown in Fig. 9. There are three measurement processes in the obtained sequence. First, SRV0 is measured after it has been machined. SRV1 is measured after SRV1 and SRV2 have been machined. Finally, SRV2, SRV3, and SRV4 are measured after SRV3 and SRV4 have been machined. Since SRV0 has a subordination relationship with SRV1, which is the next process, the obtained sequence is valid. Since SRV1 has a subordination relationship with SRV3 and SRV4, SRV1 is measured after SRV1 has been machined. However, the tool to be used for SRV2, which is the next process after SRV1, is the same as the tool to be used for SRV1. Therefore, SRV1 is measured after SRV2 has been machined and the obtained sequence is valid. Since SRV2, SRV3, and SRV4 are at the bottom of the association chart, they are measured after all SRVs have been machined, and the sequence is valid. The present study mainly aims to realize an autonomous manufacturing, in which the machining sequence is not stopped by the machining abnormalities. Since SRV2, SRV3 and SRV4 do not affect machining in the next process, the machining abnormalities rarely occur the machining interruption in the next process. Therefore, the measurement is not absolutely necessary on machine. The results show that measurement planning can be automatically performed based on the association chart.

We next verified the method for detecting machining abnormalities and the use of re-machining. Excess cutting and incomplete cutting were considered.

4.2 Validation of excess cutting detection

In order to validate the detection of excess cutting, SRV1 was machined using a square end mill with a diameter of 8 mm instead of 6 mm. The tolerance was assumed to be 0.5 mm. Machining was stopped because the measurement of SRV1 indicated excess cutting. Figure 10 shows the obtained machining and measurement sequence. Figure 11 shows the probe path for the measurement of SRV0 after SRV had been machined and the measurement of SRV1 before machining was stopped. Figure 12 shows the machined workpiece after the machining was stopped. These results show that the proposed system can automatically stop machining when excess cutting is detected. The proposed system can thus reduce wasted machining because machining abnormalities can be detected early.
4.3 Validation of incomplete cutting detection

In order to validate the detection of incomplete cutting, SRV0 was machined using a square end mill with diameter of 6 mm instead of 8 mm. The tolerance was assumed to be 0.5 mm. The measurement of SRV0 indicated incomplete cutting and thus SRV0 was re-machined after a tool change. Figure 13 shows the obtained machining sequence, measurement planning, and automatic re-machining based on the measurement results. Figure 14(a) shows the workpiece for which the measurement result for SRV0 was incomplete cutting. Figure 14(b) shows the workpiece after re-machining of SRV0 and the subsequent completion of machining. This case study shows that when the measurement result is incomplete cutting, it is possible to continue machining without leaving machining abnormalities in the next process after re-machining. Figure 14(c) shows the actual path used for the whole machining. This increases the machining efficiency because machining troubles in the next process due to abnormalities in the current process are avoided.
5. Conclusion

This study proposed a system that can automatically determine measurement planning according to the geometrical constraints of the removed material. If a machining abnormality is detected based on the measurement results, the proposed system automatically judges whether to stop machining or to conduct re-machining. In order to validate the proposed system, case studies were conducted. The conclusions can be summarized as follows:

(1) The proposed system can automatically perform measurement planning. Measurement is conducted after the machining of a region that has an influence on the next machining process according to the association chart, which shows the subordination relationships of the geometrical constraints among removal volumes. Therefore, it is possible to avoid machining troubles in the next process due to abnormalities in the current process.

(2) The proposed system can automatically determine whether to stop or continue machining according to the measurement results. If measurements indicate excess cutting, the system immediately stops machining because it is impossible for the workpiece to be modified. If measurements indicate incomplete cutting, the system re-machines the affected region and continues the machining process by recursively applying the NC program for the target removal volume.

The automated measurement planning for on-machine measurement and the automated re-machining proposed in this study can increase production efficiency and allow the realization of an autonomous manufacturing system.
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