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Automatic tool setting errors compensation in ultraprecision machining

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Abstract
Among the error causes affecting the machining accuracy, slight tool setting errors may have critical influence on the machining accuracy due to the miniaturization and complexity of objects to be machined. However, it is impossible to prevent the setting errors, which may increase in accordance with the number of the control axes, by manual adjustment. Thus, it is extremely difficult to locate the tool accurately while multi-axis control ultraprecision machining at the right position. Therefore, this study aims at developing a novel compensation method of tool setting errors by using an on-machine contact-type measurement device. According to the proposed method, it enables to measure and calculate the setting errors of the tool control point automatically against the center of rotational axes by simple grooving. From the experiments, it is found that the proposed method has a potential to automate the compensation procedure of the setting errors and to achieve multi-axis control ultraprecision machining.

Ultraprecision machining, Multi-axis control, On-machine measurement, Tool setting errors

1. Introduction

According to the needs of high performance electronic and/or optical devices, a development of highly integrated ultraprecision machining technology is strongly required in order to fabricate the tiny and complicated shapes with high accuracy. To meet the requirements, the authors have developed some cutting methods to fabricate the microparts by means of diamond cutting tools installed on a multi-axis ultraprecision machining center [1, 2]. However, serious problems caused by the accumulation of various kind of errors happened in the fabrication, and deteriorated the accuracy of the machined shapes.

From the nature of multi-axis control ultraprecision machining, all sorts of errors greatly affect the machining accuracy even if they are very small. The error causes affecting the machining accuracy are tool configuration, tool setting, machine tool, material to be machined, cutting condition and so on. Among them, slight tool setting errors may have critical influence on the machining accuracy due to the miniaturization and complexity of objects to be machined. However, it is impossible to prevent the setting errors, which may increase in accordance with the number of the control axes. Thus, it is extremely difficult to locate the tool accurately while multi-axis control ultraprecision machining at the right position.

The authors have been conducting 5-axis control ultraprecision machining by using a non-rotational cutting tool based on tool setting errors compensation [3]. In this method, the workpiece have to be removed from the machining center after test cutting in order to measure the grooves created for detecting the tool actual position and calculating the setting errors. However, when the workpiece is removed even once, it cannot be replaced again at the same position. And it is difficult to automate the compensation procedure of the setting errors. In order to solve these problems mentioned above, it is required to observe the workpiece without removing from a machining center and to shorten the compensation time.

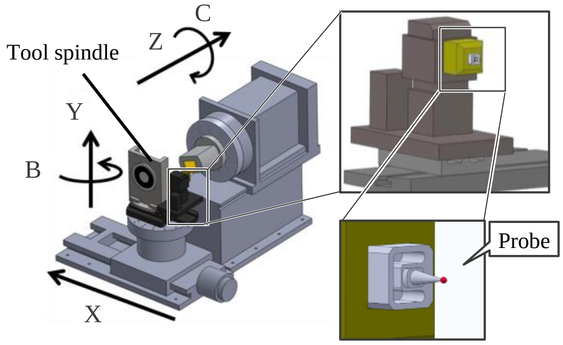
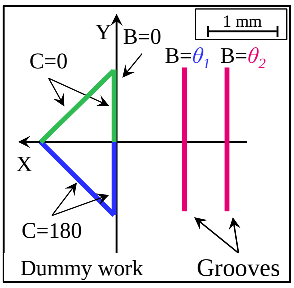


Figure 1. Ultraprecision machining center equipped with on-machine measurement device

2. Experimental setup

Figure 1 illustrates a 5-axis control ultraprecision machining center that is used in the study of ROBOnano Ui made by FANUC corp., which is equipped with three translational axes (X, Y, Z) and corresponding three rotational axes (B, C). The resolutions of the translational axes and the rotational axes are 1 nm and 0.00001 degrees, respectively. NC data is generated where the tool control point would be located on the center of rotational axes as a tool initial position. However, it is extremely difficult to precisely locate the control point on the axes since the initial tool is set by rough measurement and manual adjustment. This results in the deterioration of machining accuracy. Thus, the compensation method is devised to reduce the influence of tool setting errors.

A contact type on-machine measurement device is controlled by NC controller and mounted on B table beside a turbine spindle. The device NANOCHECKER is made by FANUC corp, and also has 1 nm resolution. It is confirmed that the performance is little different from commercial contact type measurement equipment. The workpiece is set up on C table. To measure the created groove depth and dimension, the displacement of the probe which contacts the workpiece surface is recorded in a PC as the coordinate V.



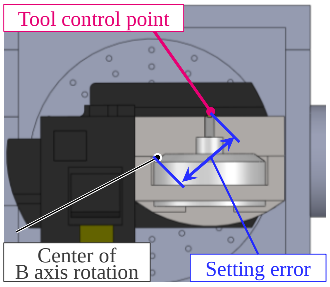


Figure 2a. Grooved simple shape errors

Figure 2b. An example of setting

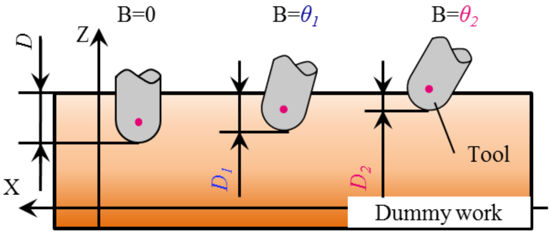


Figure 3. Grooving for detecting setting errors against B axis

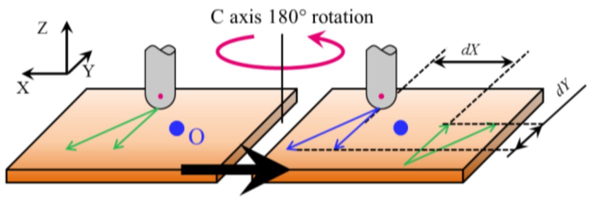


Figure 4. Grooving for detecting setting errors against C axis

3. Automatic tool setting errors compensation

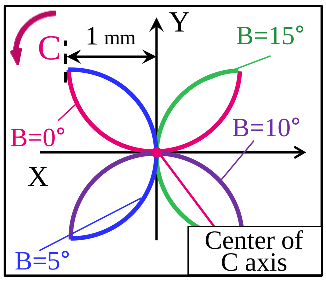
The proposed compensation method of tool setting errors has three stages. At the first stage, the simple grooves are created on a plane surface of soft material such as brass, as shown in Figure 2. At the second stage, the setting errors are calculated by detecting the positional relation between the grooves. The coordinate values of the actual tool control point can be measured by scanning the groove profiles to determine those depths. At the third stage, compensated NC data are generated based on the estimated setting errors.

As shown in Fig. 3, the tool control point has to agree with the rotational center of B table. In order to detect the setting errors, a cutting tool is fed in Z direction to create grooves, while inclining the cutting tool by specific angles B = θ_1 and θ_2 and keeping C axis 0 degree. If the tool control point does not correspond to the rotational center of B axis, X and Z coordinates of NC fata should be modified because the movement of the tool axis is limited to Z-X plane. Then the tool setting errors, ΔX and ΔZ, can be obtained based on the difference of these groove depths shown in Fig. 4. The compensation procedure is carried out by cancelling the amount of setting errors from original NC data as follows.

$$\Delta X = \frac{(D_1-D)(1-cos\theta_1)-(D_2-D)(1-cos\theta_1)}{sin\theta_1(1-cos\theta_2)-sin\theta_2(1-cos\theta_1)} \quad (1)$$

$$\Delta Z = \frac{-(D_1-D)sin\theta_2+(D_2-D)sin\theta_1}{sin\theta_1(1-cos\theta_2)-sin\theta_2(1-cos\theta_1)} \quad (2)$$

The tool control point also has to agree with the rotational center of C table. The compensation is similar to that in B axis. The setting errors caused by the difference between the tool control point and C axis are limited to X-Y plane. The grooving procedure for detecting the setting errors against C axis is illustrated in Fig. 5. At first, a cutting tool is fed in Z direction with the depth of cut D, and fed on X-Y plane to create two grooves sharing start points, while keeping B axis in 0 degree.



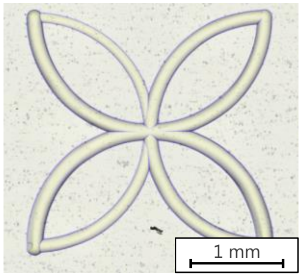


Figure 5a. Target shape

Figure 5b. Machining result

After C axis is rotated by 180 degrees, the tool creates the same two grooves. The tool setting errors *dX* and *dY* against C axis are measured by the positional relations between these machined grooves. Then, the tool control point can be accurately arranged by compensating *dX* and *dY* on NC data.

4. Machining experiment and result

In order to confirm the above mentioned compensation method, machining experiments are conducted by using a pseudo ball end mill made of single crystal diamond having a 0.5 mm radius, and an aluminum plate is used for both dummy work and workpiece. After the automatic compensation proposed in this study, complicated grooves shown in Fig. 6 are fabricated using the same cutting tool. The shape consists of four half circles with the radius of 1 mm, where the ideal depth of cut is 5 µm and B axis is rotated to be 0°, 5°, 10° and 15° for each grooving. Therefore, if the compensation of B axis is not adequate, the depth of cut varies at each groove. Moreover, if the compensation of C axis is not adequate, four half circles would not cross at the same point.

Figure 7 is the microscopic image of the machined shapes with compensated NC data. It is found that the setting errors of C axis are successfully compensated because those grooves seem to be at the target positions. Additionally, the setting errors of B axis are also successfully compensated well because those groove depths are almost same and the difference is less than 1 µm from the target depth around the cross point.

5. Conclusion

In this study, a method to compensate tool setting errors by using an on-machine measurement device is considered in 5-axis control ultraprecision machining. According to the proposed method, it enables to measure and calculate the setting errors of the tool control point against the center of rotational axes by simple grooving. From an experiment, it is found that the proposed compensation method has a potential to automate the compensation procedure of the setting errors.

Acknowledgements

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