euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

A newly method for testing the accuracy of 5-axis machining centers using cube and dot machining processes

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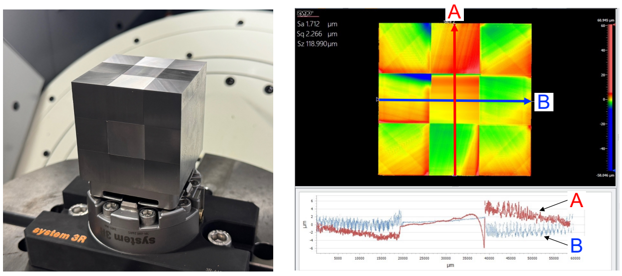
Abstract
In this paper, cube and dot machining is proposed as one of the newly accuracy test methods for 5-axis machining centers (5-axis MC). In cube machining, nine divided square areas of the cubic surface are planned by ball-nose end mill with different tool postures. The geometric errors of the 5-axis MC affect the machined surface differently for each tool posture, nine square machined surfaces are tilted and there are height differences and horizontal alignment errors between them. The geometric errors of the 5-axis MC are identified by evaluating the amount of alignment errors that occurs between nine machined squares.
For each planed square, dot machining which are formed five hemispherical cutting marks is performed by the tool is fed perpendicularly to each square machined surface maintaining the tool posture that created the square. The dots serve as markers to indicate the location of nine squares and are used to measure the relative alignment errors between the nine squares.
In this study, a mathematical model of cube and dot machining on a trunnion type 5-axis MC with an axis configuration defined as the structure code: W/CBY0XZ/T based on form-shaping-theory was developed and the machined surface was simulated. A method to identify the nine structure errors of the trunnion type 5-axis MC was studied by measuring the inclination and relative alignment errors of each square machined surface using dots on them as measuring points and comparing these measured lengths.

5-axis Machining Center, Cube Machining, Dot Machining, Accuracy Tests, Structure Errors, Form-Shaping-Theory

1. Introduction

The accuracy evaluation method for 5-axis machining centers (5-axis MC) has long been typified by cone-frustum cutting of the NAS 979 [1,2]. In recent years, new machining test methods have been proposed, such as S-shape cutting test [3]. Authors have proposed cube machining [4,5], in which nine square faces are machined at different tool postures on each face of the cube shown in Figure 1 (a). It is performed with as few thermal issues as possible, for example, rotate the spindle at the same speed as the machining conditions during warm-up operation. The influence of the error factors were assumed to be measured as the height difference between the nine surfaces, but were also observed to affect the inclination and horizontal alignment error of the squares, as shown in Figure 1 (b). In this paper, machined surface evaluation method is proposed in which dot machining is added as a measurement point for deformation and alignment error of square due to machining errors. The relationship between machining error and structure error is formulated and method of identifying structure errors using dots is discussed.



(a) Cube workpiece (STAVAX) (b) Measurement result of top surface
[Depth of cut 0.01 mm, Pick feed 0.03 mm,
Tool radius of cBN ball-nose end mill 1 mm]
Figure 1. Cube machined surface of actual machining

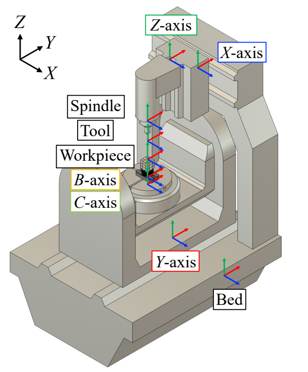
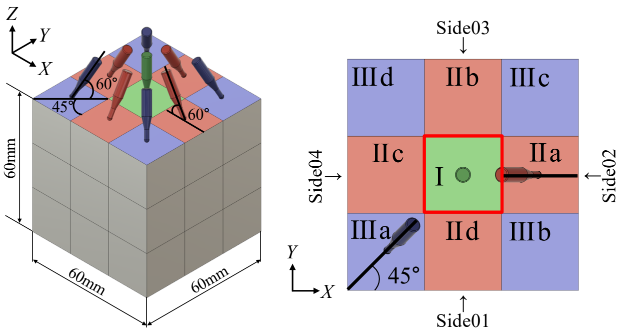


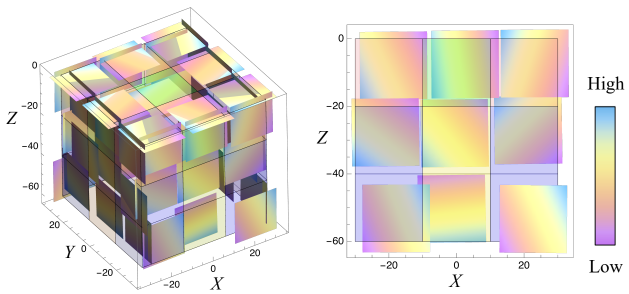
Figure 2. Form-shaping system of trunnion type 5-axis MC

Table 1 Structure errors of trunnion type 5-axis MC

Symbol	Description
δx_{CB}	Positional error of C and B-axis along X direction
α_{CB}	Orientation error between C and B-axis around X-axis
α_{BY}	Orientation error between B and Y-axis around X-axis
γ_{BY}	Orientation error between B and Y-axis around Z-axis
α_{YX}	Orientation error between Y and X-axis around X-axis
γ_{YX}	Orientation error between Y and X-axis around Z-axis
β_{XZ}	Orientation error between X and Z-axis around Y-axis
α_{ZS}	Orientation error between Z-axis and Spindle around X-axis
β_{ZS}	Orientation error between Z-axis and Spindle around Y-axis

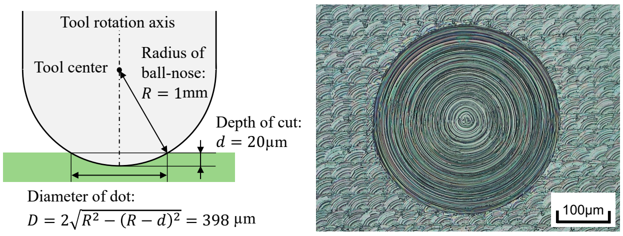


(a) Tool postures (b) Top surface sections
Figure 3. Top surface of the cube machining



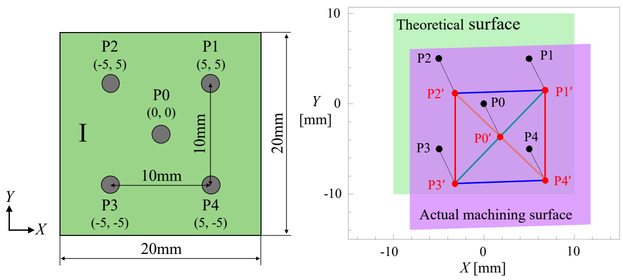
(a) Overall view (b) Side surface

Figure 4. Simulation result of cube machining



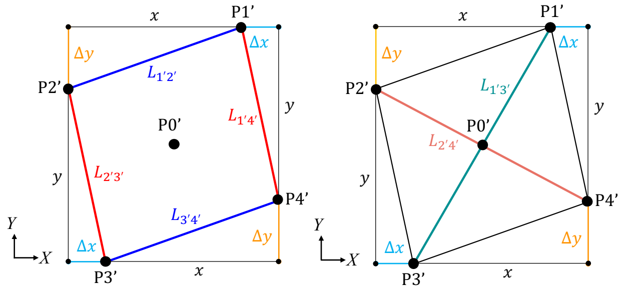
(a) Tool and dot dimensions (b) Actual machined dot

Figure 5. Dot machining of the zone I on the top surface



(a) Dots on the zone I (b) Effect of γ_{YX} on the zone I

Figure 6. Definition and simulation result of cube and dot machining



(a) Side length of parallelogram (b) Diagonal line of parallelogram

Figure 7. Effect of structure error on dots

2. Simulation of cube and dot machining

The trunnion table type 5-axis MC shown in Figure 2 has nine structure errors shown in Table 1. Cube is in the center of the table. This 5-axis MC is mathematically modelled [4,5] to simulate the cube machined surface under the conditions shown in Figure 3. The simulation results are shown in Figure 4. The inclination and vertically and horizontal alignment errors of the nine squares are observed. In conventional cube machining, the inclination of the squares and the overlap of the surfaces make it difficult to measure the alignment error. To solve this problem, dots are added to each surface and their distances are measured.

Dot machining is performed by maintaining the tool posture that created the machined surface and cutting with a ball-nose end mill from the vertical direction of the machined surface to create a hemispherical cutting mark. Based on the relationship shown in Figure 5 (a), the theoretical diameter is D = 398 μm. Figure 5 (b) shows the actual dots on the cube machined surface of tool posture 90° as observed with a digital microscope. It is identifiable enough.

Five dots are machined on each of the nine machined squares of 20 mm per side. Figure 6 (a) shows the cube top surface center zone I as an example. The five dots machined at the same tool posture are presumed to be identical, independent of the position at which they are machined. By measuring the dots on nine squares, it is possible to evaluate the deformation of the squares and the relative alignment error between the surfaces based on the distance between the dots.

The effect of γ_{YX} in zone I is shown in Figure 6 (b). The positions of the dots P0'-P4', considering the error, varied from the theoretical dot positions P0-P4, and the relative distances between the dots varied from the theoretical values.

3. Identification of structure error γ_{YX}

Identification of structure error γ_{YX} from simulation results in Zone I. In the *XY* plane of the workpiece coordinate system, focus on a rectangle consisting of four points P1'-P4'. The lengths of the sides $L_{1'2'}$, $L_{3'4'}$, $L_{1'4'}$, and $L_{2'3'}$ are theoretical values. The displacement 10 mm in the *X* or *Y*-axis were transferred to them. The difference in the lengths of the diagonals is expressed in Equation (1). The magnitude of γ_{YX} is specified from Equation (2). However, the error in the *Z* direction is a higher order term and its effect on the length is only a few nm, so it is excluded from the equation.

$$\begin{aligned} &L_{1'3'}{}^2 - L_{2'4'}{}^2 \\ &= (x-\Delta x)^2 + (y+\Delta y)^2 - (x+\Delta x)^2 - (y-\Delta y)^2 \\ &= 4x(-10.000\gamma_{BY} + 10.000\gamma_{BY} + 10.000\gamma_{YX}) \\ &= 400.000\gamma_{YX} \end{aligned} \quad (1)$$

$$\gamma_{YX} = \left(L_{1'3'}{}^2 - L_{2'4'}{}^2\right)/400.000 \quad (2)$$

4. Summary

The following results were obtained from the simulation of cube machining with the addition of dots at the measuring points on a 5-axis MC.

(1) Measuring height differences in conventional cube machining is difficult and insufficient for accuracy test.
(2) The addition of dot machining each cube machined square was confirmed to be effective in identifying structure errors because the deformation and horizontal alignment error of the squares could be evaluated.

Acknowledgments

This research was supported by JSPS Grant-in-Aid for Scientific Research (B) 23K22653 and the Project Research RU-10 in FY2020 from Machine Tool Engineering Foundation.

References

[1] ISO 10791-7: 2020, Test conditions for machining centres -Part 7: Accuracy of finished test pieces

[2] S Keaveney, P Connolly, E Ahearne and G Byrne 2014 Investigation of a Multi-Cone Variant of the Standard Cone Frustum Test for 5-Axis Machine Tools *Procedia CIRP* **14** 317-322

[3] W Wang, Z Jiang, W Tao, W Zhuang 2015 A new test part to identify performance of five-axis machine tool–part I: geometrical and kinematic characteristics of S part *Int J Adv Manuf Technol* **79** 1–10

[4] S Sakamoto, A Yokoyama, K Nakayasu, T Suzuki, S Koike and R Sato 2020 Accuracy evaluation method on the five-axis machining centers by Square 3×3 machining *Proceedings of the 18th International Conference on Precision Engineering*

[5] Z Li, R Sato, K Shirase and S Sakamoto 2021 Study on the influence of geometric errors in rotary axes on cubic-machining test considering the workpiece coordinate system *Precision Engineering* **71** 36-46