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Examination of cube machining test conditions that reveal the machine tool's motion accuracy

Sota Kawakami[1], Yukitoshi Ihara[1], Shigehiko Sakamoto[2], Hideharu Kato[2], Ryuta Sato[3]

[1]*Department of Mechanical Engineering, Osaka Institute of Technology, Japan,*
[2]*Department of Mechanical Engineering, Kanazawa Institute of Technology, Japan,*
[3]*Graduate School of Engineering, Nagoya University, Japan*

yukitoshi.ihara@oit.ac.jp

Abstract

Many methods have been proposed for testing the motion accuracy of five-axis machining centres. One of the methods is the cube machining test, in which the faces of a cube are divided into nine parts and machined with different tool orientations, i. e. different angle of the rotary axes. This test method is often shown at machine tool exhibitions to demonstrate the high accuracy of a machine, but it cannot be used as a benchmark test for a machine because not only the tool orientation but also the cutting tools itself, workpiece material, and other methods are not standardized among the exhibiting companies. However, this method has the advantage that the overall performance of the machine can be seen at a glance, as it is very similar to the conditions used in die and mould machining. In this study, various machining conditions for a medium-sized 5-axis machining centre to are investigated to eliminate the effect of spindle performance due to long machining times and to make the steps between the nine faces caused by the geometric error of the machine as obvious as possible. As a result, we propose to machine the workpiece with a size of 300 mm cube using a workpiece material for plastic moulds with an R3 ball end mill with bidirectional feed.

Keywords: five-axis machining centre, finished test piece, motion accuracy, cube machining test

1. Introduction

Five-axis machining centers are increasingly being applied to the machining of complex shapes and free-form surfaces because of their ability to simultaneously control the position and orientation between tool and workpiece. However, compared to conventional 3-axis machine tools, 5-axis machining centers (MCs) are composed of three linear axes and two rotary axes, resulting in more geometric errors, which makes high-precision machining more difficult than with 3-axis machine tools. Therefore, it is necessary to evaluate the overall performance of 5-axis machining centers.

Methods to evaluate the performance of 5-axis machining centers can be classified into non-machining methods and machining-based methods. In the former method, which are specified in ISO 10791-6[1], a ball bar and R-test device are used to measure the relative position between the spindle and the workpiece. The latter methods include the conical machining test specified in ISO10791-7[2] and the cube machining test, which has become common recently at machine tool exhibitions such as EMO and JIMTOF to show the performance of 5-axis MCs. Figure 1 shows samples done by machine tool builders.

The cube machining test has the potential to be an effective evaluation method in industry because it does not require a dedicated measuring device such as the non-machining method, and can be measured with ordinary measuring devices used in production sites. On the other hand, since each company or researcher is currently performing this test method independently, no clear test method has been defined.

Therefore, with the ultimate goal of establishing a test method, this study examined the parameters that may affect the test results and explored the causes of errors based on the results on the machined surface.

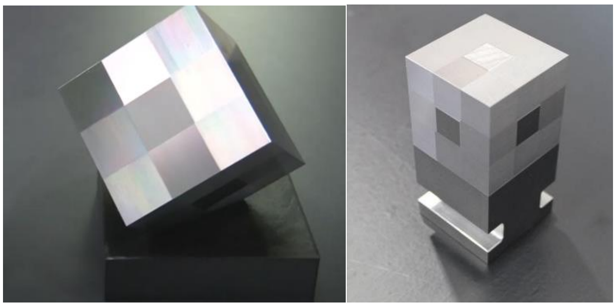

Figure 1. Examples of cube machining test

2. Cube machining test

2.1. Possible test parameters for the cube machining test

The cube machining test divides a cubic surface into nine parts, each of which is machined with a ball end mill at a different tool orientation, and evaluates the overall performance of the machine tool based on the difference in height and inclination between the machined surface areas after machining. Therefore, if machining is performed in the absence of errors, no difference in the height of the machined surface occurs. In reality, however, differences in height occur between regions due to factors such as spindle performance, geometric error, dynamic error, and the machining process.

There are a variety of test parameters, but some of the most common are workpiece size and workpiece material, rotary axis angle, mounting position, machining process, and tooling. Since the above test parameters are considered, it is necessary to examine how each of them affects the machined surface.

Considering the test parameters listed above, how they affect the machined surface will be examined.

2.2. Size and material of test piece

The test piece is assumed to be a cube like a Rubik's Cube or a dice, so it has a total of six square faces. One of the faces cannot be machined because it is attached to a table, but the other five faces are divided into nine equal parts, and each is machined with a different tool orientation.

The size of the tested machine varies. Since this test is a 5-axis machining, if a workpiece is too large, it will be difficult to change the tool orientation and machine it. The size of the workpiece is directly related to the machining time, and as the machining time becomes longer, the temparature of various parts of the machine rise, causing thermal deformation, which has a significant impact on machining accuracy, such as the elongation of the spindle, so we will be sensitive to verify the effects of heat. In the samples shown in Figure 1, one side is 60 mm to 120 mm, but in cases where a large workpiece is used, there are examples where the machining of five sides takes more than six hours. Since the purpose of this study is to propose a standard test method, we propose a cube with a side of 30 mm that can be machined with a general small 5-axis machining center. The machining time for this is about 13 minutes per face. Even in this case, the effect of the spindle performance due to long operating times on the test results cannot be ignored.

The material of the workpiece is determined by taking into account the material of the cutting tool, but since the typical processing in which the surface is machined with a ball end mill, as in this test, is die & mold processing, it is thought that it is better not to use a material that is too soft. This is because the purpose of this test method cannot be achieved if the surface roughness is greater than the step between adjacent machined zone. In conclusion, we propose carbon steel for use in plastic molds, for example BH13 in BS or H13 in ASTM. If the appropriate tool is used and the cutting conditions are appropriate, a machined surface with very small surface roughness can be obtained. Another candidate is brass, which can be cut smoothly.

2.3. Cutting tool

Since the plane is generated using a ball end mill, the larger the tool diameter, the smaller the surface roughness will be, and the larger the pick feed of the tool will be, which will shorten the machining time. Since machining time is an critical factor in this test, too small cutting tools should not be used unless testing the spindle for a long period of time.

However, in this test, the accuracy of the tool tip R shape is important. The diameter of the ball end mill used this time is 6 mm (R3), but the accuracy of the tip of a typical product is 3 to 5 µm. However, if such kind of cutting tool is used, simply changing the inclination of the tool will result in a step of 3 to 5 µm. This will not achieve the purpose of testing the machine itself, so it is necessary to select and use tools with good R contour shape. Cutting tools with good R contour shape are commonly sold, and their accuracy is 1 µm. Tools with large diameters are expensive, and it is difficult to improve the R contour shape over the entire surface, so tools with too large diameters cannot be used.

2.4. Feed direction and tool inclination angle

When cutting a surface with the tip of a ball end mill, unidirectional feed and bidirectional feed are possible. With unidirectional feed, the tool is moved away from the surface each time, which results in a longer processing time to machine one surface. However, it is common knowledge that a machine is more accurate with unidirectional feed than with bidirectional feed, and for machines with large backlash, unidirectional feed is better[3]. For the purpose of this test, it is best to use bidirectional feed to keep the processing time as short as possible.

It is also necessary to consider in which direction and by how much to tilt the tool. It is best to avoid machining with the tip of a ball end mill, as the cutting speed is determined only by the feed, but it is necessary to balance the advantage of tilting the tool, which increases the cutting speed as you get closer to the outer periphery, against the disadvantage of the entire tool bending and smaller cutting depth. Also, even if the same inclination is used relative to the plane, the amount of the tool bending will be slightly different depending on whether the tool is fed in the thrust direction, the pull direction, or to the left or right. For these reasons, it is important to perform sufficient pre-machining and make the finishing depth of cut quite small, otherwise characteristics other than the geometric error of the machine will become apparent.

In most 5-axis MCs, the angle of the tool relative to the machining surface is given by the tilt axis. By increasing the angle of the tilt axis, it is thought that the error will be larger, so it may be possible to consider the effects of positioning errors and assembly errors, but many machines have limitations on the angle range of the tilt axis.

2.5. Position to place the test piece

By changing the mounting position of the workpiece away from the center of the table (away from the rotating C-axis), it is thought that the error will be more pronounced, so it is possible to consider the effects of positioning errors and assembly errors.

However, it is common for workpieces to be placed in the center of the table, not just in 5-axis MCs with rotary tables. In the case of cube machining tests, it is considered that machining will be performed by tilting the tool, so if machining is performed in the corner of the machineable area, the cutting tool cannot be tilted freely. It seems better to set this parameter based on the premise that machining will be performed at the center of the table.

2.6. Machining conditions on the side of a cube

In addition to the top surface, there are four other sides given to cube machining. Using these surfaces, various additional conditions can be considered. However, the only fundamental difference in the machine motion conditions for machining the four sides of a cube is the positioning angle of the axis that rotates 360°, such as the angle of the rotary table in table-swivel type 5-axis machining center. Since this rotary axis generally does not contain a large error, there is not very meaningful to repeat similar conditions on all four sides.

Therefore, it is possible to use the remaining four sides to change the tilt axis angle and perform machining. We look forward to future research on this condition.

3. Cutting test using conditions from previous studies

Based on the above considerations, the standard conditions for cube machining tests proposed by Sakamoto et al. using an actual machine is investigated[4-6]. Regarding the orientation of the cutting tool, in ZONE I in the center, the tool cuts in a perpendicular position to the surface. In ZONE II, which is located above, below, left and right of ZONE I, the tool is tilted 30° relative to the Z-axis, and in ZONE III, which is diagonally from ZONE I, the tool is further rotated 45° around the Z-axis. Figure 2 shows the tool orientation under standard conditions, while Table 1 shows the angle position of rotary axes of the machine and machining sequence.

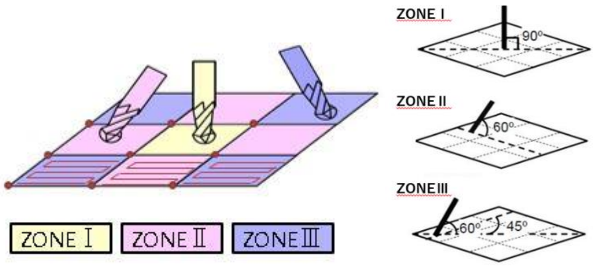

Figure 2. Tool orientation under standard conditions

The machine tested was a 5-axis MC with a rotary table, and its configuration of axes is shown in Figure 3. The basic specifications are shown in Table 2. The main conditions for cutting operations are as follows: Workpiece: Carbon steel for molds (SKD61 in JIS, aproximately equivalent to H13), End mill: R3 Carbide alloy, Spindle speed: 16 000 mm/min, Feed speed: 930 mm/min, Depth of cut: 0.1 mm, Pitch: 0.1 mm, Processing time: 13 min 4.7 s. Figure 4 shows the tool path used in this test.

Table 1 Angle of Rotary axes and machining sequence

	ZONE I	ZONE II	ZONE III
Machining sequence	1	1, 2, 3, 4 (2, 3, 4, 5)	1, 2, 3, 4 (6, 7, 8, 9)
Rotary axis C [°]	0	0, 90, 180, 270	45, 135, 225, 315
Tilting axis A [°]	0	-30	-30

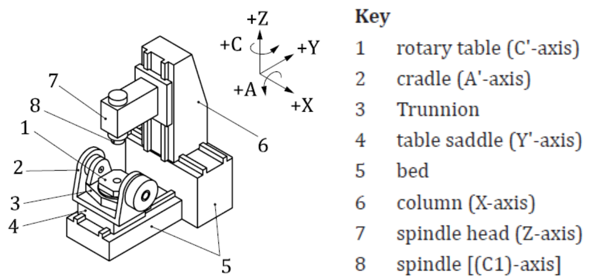

Figure 3. Configuration of axes of the machine tested[1]

Table 2 Basic specifications of the machine tested

Moving range of linear axes X, Y, Z [mm]	750, 650, 560
Moving range of rotary axes A, C [°]	-120 ~ 120, 360
Size of rotary table [mm]	∅650
Maximum spindle rotating speed [min-1]	20 000

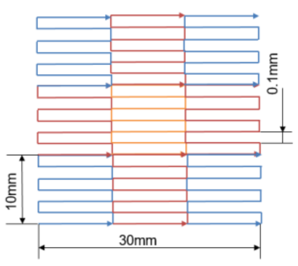

Figure 4. Tool path

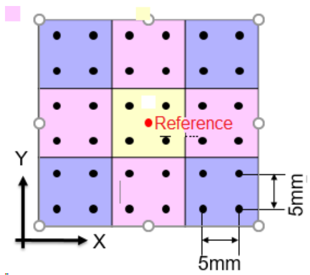

Figure 5. Measured point

4. Cutting test results

The purpose of this test is to find machine errors appear as steps and inclinations between each machined flat surface, however, this time the heights of four points on each flat surface were measured, for a total of 36 points, and the average of the four points was taken to evaluate only the height (step) of each flat surface. There are various measuring devices and methods that can be used to measure the results of machining, and for accurate machining results it is best to use a contour measuring machine that can also measure surface roughness, but in this experiment the workpiece was not removed after machining, and four-point measurements of each surface were repeated five times with a touch probe. The measuring point is shown in Figure 5.

The experiment was repeated several times by changing the cutting sequence and by placing the machining position away from the center of the table. A typical result is shown in Figure 6. The surface roughness of the machined surface was approximately *Ra* = 0.5 µm, and the height of each zone was within ±5 µm. In addition to the touch probe, on-machine measurements were also performed using a lever type LVDT, and as the measurement error was only 1 to 2µm, it can be determined that the experimental results were meaningful, but it is still not possible to determine where the geometric error of the machine lies from these results. More details will be given in the next chapter.

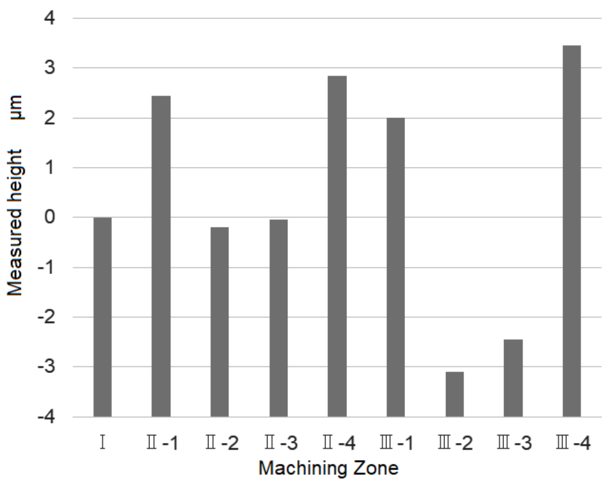

Figure 6. Typical test result

5. Observations

Since the plane is generated using a ball end mill, the larger the tool diameter, the smaller the surface roughness will be, and the larger the pick feed of the tool will be, which will shorten the machining time. Since machining time is an critical factor in this test, too small cutting tools should not be used unless testing the spindle for a long period of time.

What can be seen from Figure 6 is that in ZONE II, II-1 and -4 are high, and II-2 and -3 are low. Furthermore, in ZONE III, III-1 and -4 are high, and III-2 and -3 are low. Figure 7 shows the state of the machine's tilt axis (A-axis). At this time, the A-axis is kept at -30°, and machining is performed with different table (C-axis) rotation angles. Figure7 is a diagram of an experiment in which the workpiece mounting position is away from the table center. If the machining position is away from the table center like this, the machining results above and to the left of the table center will be lower, and this is thought to be due to the angular deviation of the C-axis and Z-axis (i.e. the angular positioning error of the A-axis), but as mentioned above, changing the mounting position of the workpiece on the table did not change the results very much.

As can be seen from Figure 7, under standard conditions, the angle of the tilt axis (A-axis in this case) is -30°, and machining is only performed at a constant angle position except for ZONE I. This is not good for the performance test of the rotary axis of a five-axis machining center. This time, only the test conditions for the top surface of the cube machining is considered and examined, but as mentioned at the beginning, a cube has a total of five faces. From what have seen at exhibitions and so on, various conditions have been proposed, but as this time, there is not much movement of the tilt axis is found, so we would like to propose conditions that make it possible to machine at angles with various tilt axes by using the four side surfaces in the future.

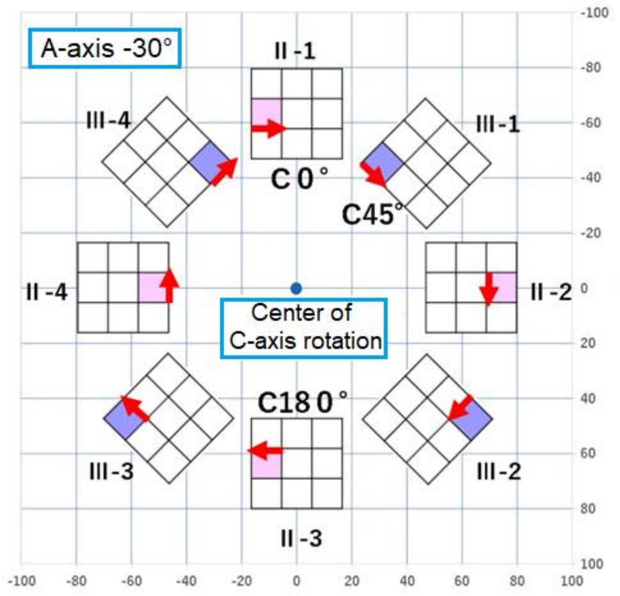

Figure 7. Machining position in ZONE II and ZONE III

6. Conclusions

After considering standardized test conditions for cube machining seen at exhibitions and other events, and conducting tests on an actual machine, the following conclusions are obtained.

- The size of the cube should be as small as 30 mm, so that it does not affect the performance of the spindle during long-term operation.
- The cutting tool should be end mill as small as around R3 with good R accuracy, and the workpiece material should be using for plastic moulds with an R3 ball end mill with bidirectional feed.we propose to machine the workpiece with a size of 30 mm with bidirectional feed.
- Under the standard conditions used in previous research, machining is performed with a constant tilt axis angle, so it is necessary to explore conditions in which machining is performed with a different tilt axis using the side of the cube.

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