Study on Machining Performance of Complex Shape Workpieces on a 5-axis Machining Center

Takayuki AKAI[*1], Mariko SASAKI[*2], Keiji OGAWA[*3], Toshiki HIROGAKI[*1], and Yoshiaki KAKINO[*4]

[*1]Doshisha University, Graduate School, Mechanical Engineering

(Miyakodani 1-3,Tatara, Kyoutanabe, Kyoto, 610-0321, Japan)

[*2]DMG Mori Seiki Co., LTD (362 Idono-cho, Yamato-Koriyama City, Nara 639-1183, Japan)

[*3]The University of Shiga Prefecture ,School of Engineering

(2500, Hassaka-cho, Hikone-City, Shiga 522-8533 Japan)

[*4]Kakino Research Institute (Tamatsushima-cho 316-2, Shimogyo-ku, Kyoto 600-8427, Japan)

[Manuscript received on Feb 3, 2014；Accepted September 10,2014]

Abstract

Workpieces with various geometries are machined on 5-axis machining centers recently, and the machining accuracy and the machining efficiency of these machines have been compared with those of conventional vertical machining centers with a ball end mill cutter. These comparisons show that when a simpler- geometries workpiece is machined, both the machining accuracy and the machining efficiency are almost the same on the both machines. On the other hand, when a more complex-geometries workpiece is machined, the superior machining accuracy and machining efficiency are achieved on a 5-axis machining center. This study was conducted based on the following conditions: 1) an end mill with a smaller L (overhang length of a tool)/D (tool diameter) can be used to prevent chattering and 2) a square end mill can be used for higher feedrate cutting.

Keywords: 5-axis machining center, Simultaneous 5-axis control machining, Simultaneous 3-axis control machining, Workpiece with various complex geometry, Machining efficiency, Machined accuracy

1 INTRODUCTION

The machining performance of 5-axis machining centers has been significantly improved recently. Especially some 5-axis machining centers with the latest table-on-table structure have boasted the exceptionally excellent motion accuracy. For example, some of them have achieved the motion error of 4μm or less in the measurement by DBB5 on the XY, YZ, and ZX planes of the linear axes, which is almost equivalent to the accuracy of a high-accuracy vertical machining center (Kakino, et al., 1990, Takayama, et al., 2010). The motion error of the two rotary axes has been drastically improved as well, achieving the angular error of 2μm to 3μm/300 mm or less, which is a type of the alignment error (Takayama, et al., 2011a, 2011b, Ibaraki, et al., 2010). Measurement and compensation of the offset error have become even easier. On the other hand, almost no reports on the machining efficiency and the surface quality and machining accuracy of machined workpieces using the latest 5-axis machining centers have been presented.

We therefore determined to compare the machining efficiency and machining accuracy of a 5-axis machining center with the table-on table structure, which features its excellent motion accuracy, and a conventional vertical machining center using the three linear axes by machining a variety of truncated cones with various complexities. Compared with vertical machining centers, 5-axis machining centers are obviously more expensive because they have two rotary axes in addition to three linear axes; therefore they are supposed to demonstrate the performance worth the price difference.

Note that all the workpiece shapes that we selected can be machined on a vertical machining center. In this study, workpieces were machined on a 5-axis machining center with an equivalent accuracy to a vertical machining center, and examined how much more efficiently machining was conducted on a 5-axis machining center. To eliminate disadvantageous factors from a vertical machining center, shrinkage-fit tool holders were used for testing to enhance the gripping force.

2 GEOMETRY OF WORKPIECES TO BE MACHINED

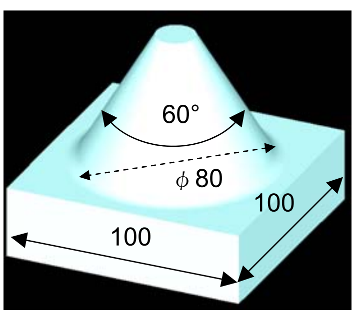
We determined to compare finished conditions of three types of workpieces shown in Fig. 1—a truncated cone and two modified truncated cones with different complexities. These workpieces are supposed to have no undercut portion because machining of a workpiece with undercut portion on a vertical machining center requires special fixtures for mounting a workpiece and rotary axes, which makes it difficult to compare finished conditions. In general the ratio of the overhang length of a tool L and the tool diameter D (L/D) is an important parameter which affects the finished conditions by end milling; therefore, we focused on L/D to proceed with this study.

2.1 Core truncated cone (in the case that the same tools with small L/D are used for machining)Core truncated cone (in the case that the same tools with small L/D are used for machining)

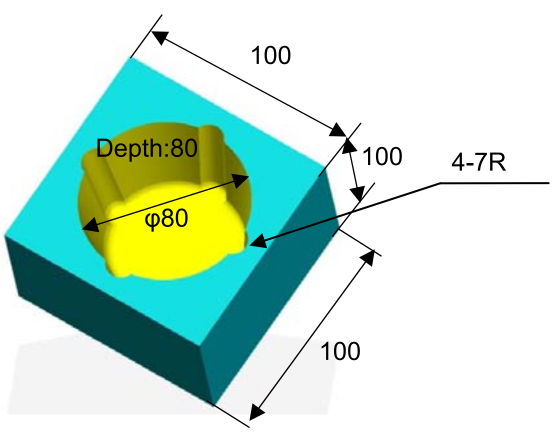
A core truncated cone shown in Fig. 1 (a) was machined with a ball end mill. The profiles of circularity at the three sections that are perpendicular to the core of this axis were compared. In the case of this geometry, the exactly same cutting conditions can be used when three linear axes are used (pattern 1) and when the rotary axis C is used (pattern 2), so only the influence by motion errors of a machine can be identified. Also, because this measurement was conducted on circular sections, the machining accuracy can be easily verified. Profiles of edge lines on finished surfaces are measured as well to compare the finished surface roughness and the straightness.

2.2 Cavity truncated cone with grooves (in the case that tools with different L/D are used for machining)

A cavity truncated cone shown in Fig. 1 (b) was machined with a ball end mill. The machining accuracy and the finished surface roughness were measured and verified in the same procedure as the truncated cone shown in Fig. 1 (a). This geometry can be also machined in simultaneous 3-axis control machining using linear axes (pattern 1) and machining using rotary axes (pattern 2). In the case of pattern 1, however, with a short overhang such as L/D = 4, the accessibility of a tool is bad and the overhang needs to be changed to L/D = 7, which deteriorates the machining efficiency and the machining accuracy. We examined the degree of the deterioration.

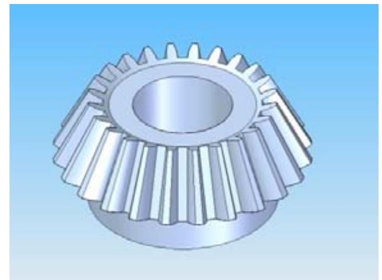


(a) Cone



(b) Cavity cone with grooves

To examine the deterioration, a workpiece with a groove circular section of 7 mm was machined.



(c) Straight bevel gear

Fig.1 Parts geometries of tested workpieces

Table 1 Specifications of Straight bevel gear

Type of gear	Straight bevel gear
Module	5
Number of teeth	17
Width of gear [mm]	38
Average cone distance [mm]	121.5
Pitch cone angle [deg.]	25.278
Material	Pre-hardened steel

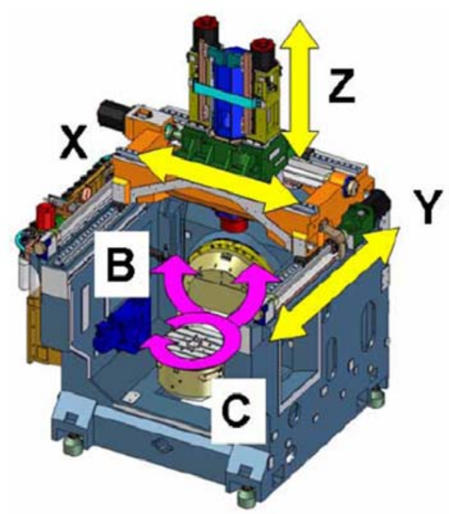
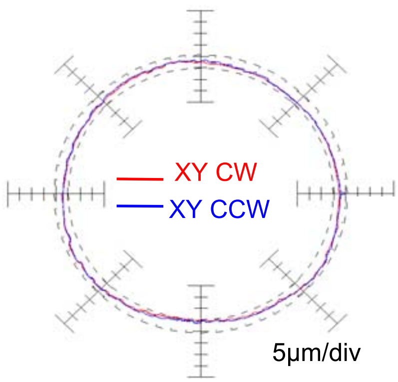


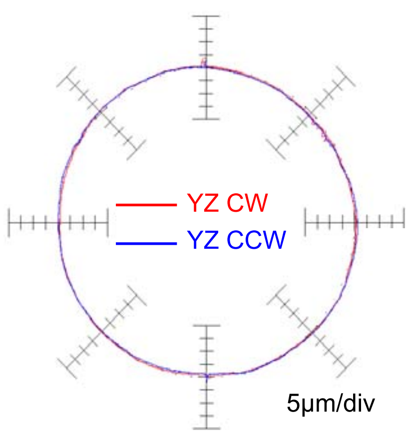
Fig.2 Outline of Structure of 5-axis machining centers(DMG Mori Seiki, NMV5000)with table-on-table type

Table 2 Specifications of 5 axis machining center(DMG Mori Seiki, NMV5000)

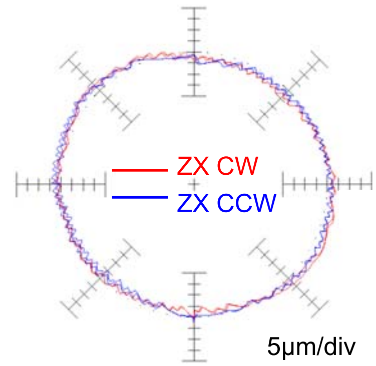
Workpiece size [mm]	700×450
Workpiece weight [kg]	300
Stroke X [mm]	730
Y [mm]	510
Z [mm]	510
Stroke of 1st rotating axis B[deg.]	-160 ～ +180
Stroke of 2nd rotating axis C [deg.]	360
Feed rate X [mm/min]	50
Y [mm/min]	50
Z [mm/min]	40
B [min^{-1}]	50
C [min^{-1}]	120
Spindle speed [min^{-1}]	12000



(a)XY plane



(b)YZ plane



(c)ZX plane

Fig.3 Motion error traces measured at individual planes with two straight motion axes drive.

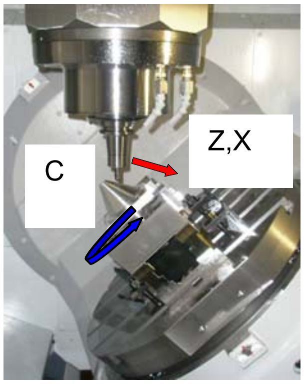
2.3 Bevel gear (3-axis machining with a ball end mill and 5-axis machining with a square end mill)

Although a large spiral bevel gear used to be machined with the dedicated machine manufactured by Klingernberg, recently it can be machined on a 5-axis machining center using a square end mill (Alves, et al., 2013, Tsuji, et al., 2011). This study examines how much the required level of the machining accuracy and the machining efficiency is achieved in machining of a bevel gear as a complex shape workpiece. Note that a compact straight bevel gear was machined to simplify this study.

The machined accuracy and the machining efficiency were compared when a bevel gear shown in Fig. 1 (c) was machined with a ball end mill using three linear axes (equivalent to machining on a vertical machining center: pattern 1) and machining with peripheral inserts of a square end mill using linear axes and rotary axes (pattern 2). As a general rule contour machining was conducted during ball end milling.

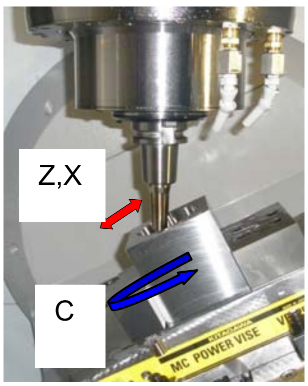
Machining a relatively hard material is vulnerable to chattering, so lowering machining conditions is the only option to avoid chattering. Even when chattering is not occurring, a tool and its supports are vulnerable to elastic deformation caused by cutting resistance, which could increase errors in machining shapes.

If we consider the above mentioned problems, machining with a square end mill is not necessarily suitable for high-efficiency machining when high profile accuracy and high finished surface quality are required. Therefore, we examined how much machining efficiency would be improved through machining of this model workpiece.



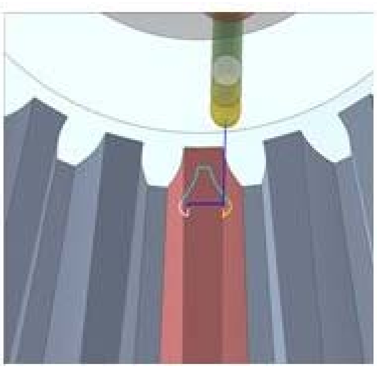
(a) Cone

(Pattern 1) 3-axis control machining with ball end mill



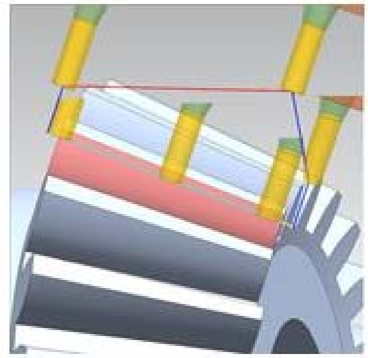
(b) Cavity cone with grooves

(Pattern 2)5-axis control machining with square end mill



(c) Straight bevel gear

(Pattern 1) 3-axis control machining with ball end mill



(Pattern 2)5-axis control machining with square end mill

Fig.4 Driven axis for the machining of workpieces with various geometries

3 MACHINE TOOLS AND EXPERIMENTAL CONDITIONS

3.1 Machine tool used in this study

Three types of workpieces shown in Fig. 1 were machined on the latest table-on-table type 5-axis machining center to compare the machining accuracy and the machining efficiency. Fig. 2 shows the structure of the machine and Table 2 shows its main specifications.

Fig. 3 shows an example of motion error locus of the linear axes (Takayama, et al., 2010). These figures clearly show that the three linear axes have the equivalent motion accuracy to high-accuracy vertical machining centers.

The motion accuracy of rotary axes is greatly affected by differences in the whole structure, the drive mechanism, and bearings. For example, the angle error, which is one of alignment errors, can be easily reduced, e.g. up to 2μm to 3μm/300 mm, with the table-on-table type machine. For detail information on measurement and compensation of each motion error, a literature (Takayama, et al., 2011b) can be referred.

3.2 Machining conditions

（1）Machining test 1 (a core truncated cone)

The machining efficiency and the machining accuracy were compared when a core truncated cone shown in Fig. 1 (a) was machined with a ball end mill using the three linear axes (equivalent to a vertical machining center: pattern 1) and when this workpiece was machined with a ball end mill using the rotary axes and the linear axes (pattern 2). Contour machining was conducted in the both patterns. The method of applying motion while machining a workpiece using the rotary axes is shown in Fig. 4 (a). The required times for machining workpieces using the three linear axes and using the rotary axes were almost the same, so only the results of finished machining were compared. The cutting conditions are as shown below.

Machining with the three linear axes (the same when using the rotary axes)

Table 3 Machining conditions (a core truncated cone)

Ball end mill	TiAlN-coated cemented carbide (two teeth)
Diameter	10 mm
Workpiece material	pre-hardened steel NAK55 (40HRC)
Overhang	70 mm (L/D = 7)
Spindle speed	6000 min^{-1}
Feedrate F	1200 mm/min
Machining method	Contour helical machining
Machining pitch	0.15 mm (cusp height = 0.5μm)
Allowance	0.1 mm

（2）Machining test 2 (a cavity truncated cone with grooves)

The machining efficiency and the machining accuracy were compared when a cavity truncated cone with grooves shown in Fig. 1 (b) was machined with a ball end mill using the three linear axes (equivalent to a vertical machining center: pattern 1) and when these workpieces are machined with a ball end mill using the rotary axes and the linear axes (pattern 2). The cutting conditions are as shown below.

Machining with the three linear axes (pattern 1)

Table 4 Machining conditions (a cavity truncated cone with grooves) (pattern 1)

Ball end mill	TiAlN-coated cemented carbide (two teeth)
Diameter	10 mm
Workpiece material	pre-hardened steel NAK55 (40HRC)
Overhang	40 mm (L/D = 4)
Spindle speed	10000 min^{-1}
Feedrate F	1000mm/min (the equal surface speed is applied by the C-axis rotation)
Machining method	Contour helical machining
Machining pitch	0.15 mm (cusp height = 0.5μm)
Allowance	0.1 mm

Machining with the rotary axes (pattern 2)

Table 5 Machining conditions (a cavity truncated cone with grooves) (pattern 2)

Overhang	40 mm (L/D = 4)
Feedrate F	2000 mm/min

Other conditions are the same as machining using the three linear axes

（3）Machining test 3 (a straight bevel gear)

The machining efficiency and the machining accuracy were compared when a bevel gear shown in Fig. 1 (c) was machined with a ball end mill using the three linear axes (equivalent to a vertical machining center: pattern 1) and when these workpieces were machined with a square end mill using the rotary axes and the linear axes (pattern 2). In ball end mill machining (pattern 2) contour machining was conducted. When the workpiece was machined with a square end mill using the tilting axis (pattern 2), the B-axis was gradually tilted from 0°to 20° One feed is equivalent to the cusp height which is the angle change of the B-axis. The method of applying motion necessary for machining is shown in Fig. 4(c). The cutting conditions are shown below.

Machining with a ball end mill using the three linear axes (pattern 1)

Table 6 Machining conditions (a straight bevel gear) (pattern 1)

Ball end mill	TiAlN-coated cemented carbide (two teeth)
Diameter	4 mm
Workpiece material	pre-hardened steel NAK55 (40HRC)
Overhang	38 mm (L/D = 9.5)
Spindle speed	6000 min^{-1}
Feedrate F	1200 mm/min
Machining pitch	0.18 mm along the finished shape (average) (cusp height: 2.6 μm—adjusted by changing the pitch)
Allowance (cutting in the radius direction)	0.1 mm
Downcut	

Machining with a square end mill using a simultaneous 5-axis machining center (pattern 2)

Table 7 Machining conditions (a straight bevel gear) (pattern 2)

Square end mill	TiAlN-coated cemented carbide (two teeth)
Diameter	4 mm
Overhang	18 mm (L/D = 4.5)
Spindle speed	6000 min^{-1}
Feedrate F	1200 mm/min
Machining pitch	The tilting angle of the B-axis was changed when moving the tool along the finished surface so that the cusp height became the same (=2.6μm) as pattern 1. (The B-axis was gradually tilted from 67.1°to 64.1°. The average tilting angle in one time was 0.035° and the average pitch along the feeding path was 0.34 mm.)
Downcut	

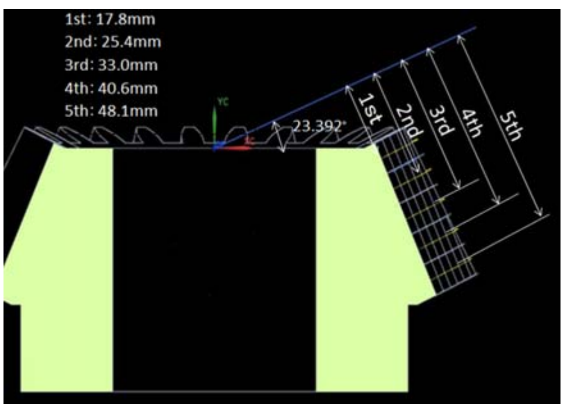


Fig.5 Measured points of machined deviation of bevel gear

When a ball end mill was used, chattering occurred with these conditions and the finished surface seemed to become rough. To determine the cutting conditions which can achieve the same level of machining geometric errors and the surface quality by ball end milling, the workpiece was machined with the feedrate and the spindle speed being reduced gradually by 10%.

Compared with the machining conditions when a square end mill was used: 50%, 40%, and 30%.

3.3 Measuring method of the machining accuracy and the finished surface roughness

The circularity, straightness, and surface quality of machined core truncated cones and cavity truncated cones with grooves were measured by using the following instruments:

Table 8 Measuring method

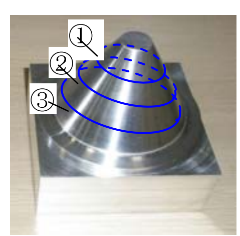
Measurement of circularity profile	Circularity measurement instrument, Talyrond290
Measurement of straightness profile	Coordinate Measuring Machine (CMM), Falcio－Apex9166
Surface roughness measuring instrument	Surface roughness tester, Form Talysurf PGI 1200

The accuracy of a bevel gear was measured by the CMM CAT-1000 in the following procedure. First, IGES-type 3D model of the bevel gear was imported to the software of the CMM manufactured by Mitutoyo and a program for measurement was created. Then the shape was measured. Differences between the designing data and the measuring data are detected by a touch probe (Mitutoyo Co., 2013). The measuring positions are shown in Fig. 5. This software allows the probe to approach the workpiece from the normal direction to the face of the flute.

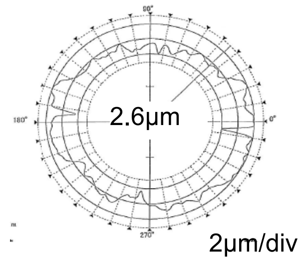
4 MACHINED RESULTS AND INTERPRETATIONS

4.1 Machining of a core truncated cone

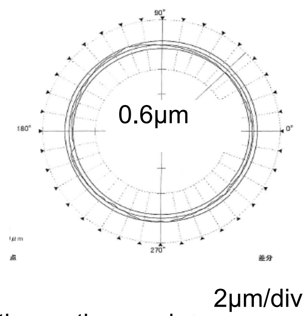
Machining time was 31 minutes 3 seconds when a core truncated cone was machined (Fig. 1 (a)) with three linear axes (pattern 1); and it was 31 minutes 32 seconds, almost the same, when the same workpiece was machined with four axes simultaneously controlled (pattern 2). It was a natural result as the cutting conditions were exactly the same. Machining time by three linear axes was slightly shorter because it took less for processing interpolation. The definition of machining time is: from pressing the NC start button after preparation till ending with an end signal upon completion of machining. Precisely speaking, the machining time is the sum of cutting time and air-cutting time. The time for changing tools is usually included in the machining time, but this particular workpiece does not require a tool change, so it is assumed as zero.



Measuring positions
Distance from the top: 25 mm

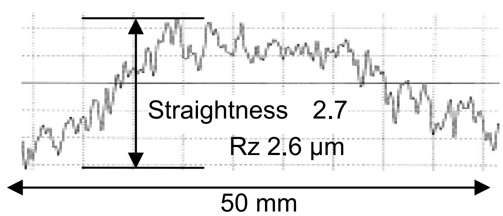


(a) Simultaneous 3-linear-axis control machining

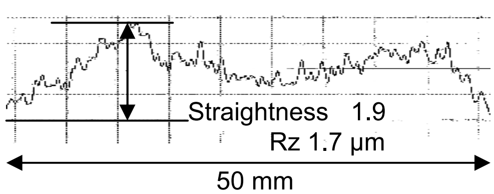


(b) Rotating motions and simultaneous 2-linear-axis control machining

Fig.6 Geometrical errors of the machined cone



(a) Simultaneous 3-linear-axis control machining



(b) Rotating motion and simultaneous 2-linear-axis control machining

Fig.7 Geometrical errors of the machined cone (straightness and surface roughness of machined cone)

Table 9 Comparison of machining accuracy and machining time (cavity cone with grooves)

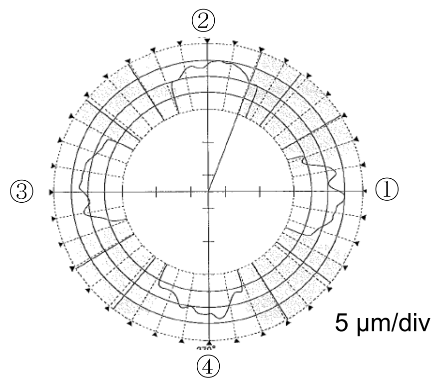
Machining method	Circularity [m]	Straight ness [m]	Surface rough ness [m]	Machin -ing time [min]
Simultaneous 3-linear-axis control machining	7.9	2.5-3.1	5.9	88.5
Rotating motion and simultaneous 2-linear-axis control machining	4.8	1.6-4.6	2.6	55.2

A workpiece was machined by two different methods to measure circularity profiles at three sections and finish profiles at three edges. Fig. 6 and Fig. 7 show the typical profiles with the values of circularity, straightness, and surface roughness.

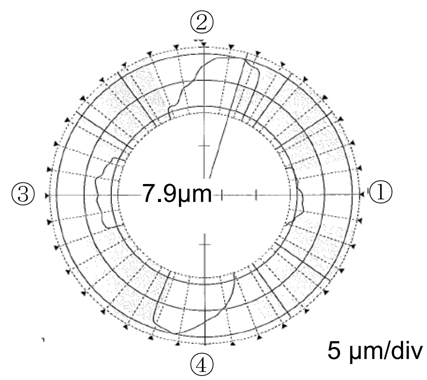
Surface roughness was around 2.6 μmRz, almost the same at any sections, while machining in two different machining methods. Circularity was as small as 3 μm even when a workpiece was machined only by linear axes with the circular interpolation (pattern 1). Whereas, with an additional rotary axis C (pattern 2), the circularity was further small as 1.2 to 1.6 μm. The farthest section from the C-axis table achieved worst circularity. It is assumed that it was caused by the C-axis angular motion.

In these two machining methods, cutting mechanism and conditions were exactly the same, therefore difference of machining profiles were actually compared between the motion errors of two linear axes in circular interpolation, and the reflectiveness of the C-axis motion errors in radial directions to the machining profile errors. Fig. 3 (a) shows a circularity error of 4 μm while machining a circle by the X- and Y-axis in circular interpolation, whereas C-axis rotation errors are around 1.5 μm in the radial directions and its smallness is a cause.

However, these machining methods are not necessarily always selected when a conical workpiece is machined using the 5-axis machining center. In other machining methods, it is not necessarily true that machining with a rotary axis always achieves higher accuracy because the machined profile errors are affected by such as moves of a cutting point on a cutting edge of a ball end mill or directions of cutting resistance.

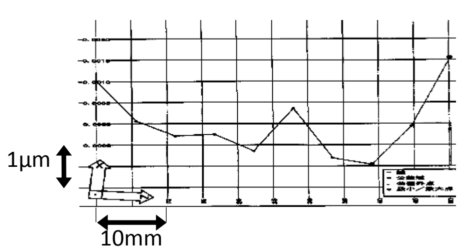


(a)Rotating motion and simultaneous 2-linear-axis control machining

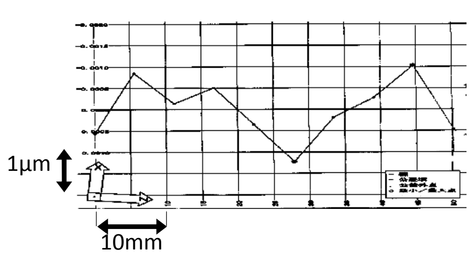


(b) Simultaneous 3-linear-axis control machining

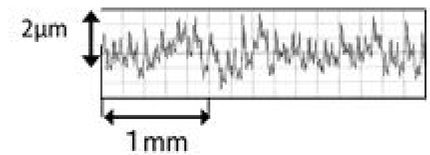
Fig. 8 Out-of-circularity of the machined cavity cone with grooves (measured at the position with 45 mm high from the bottom)



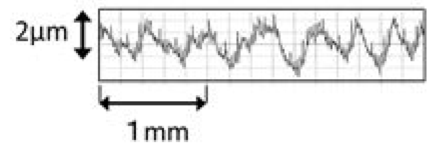
(a) Simultaneous 3-axis control machining



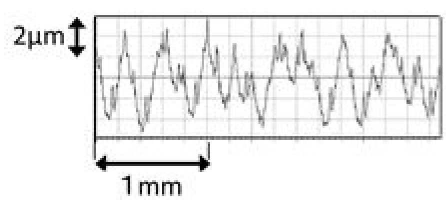
(b) Rotating motions and simultaneous 2-linear-axis control machining



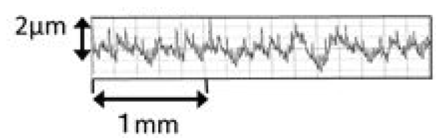
(c) Machined roughness Case 1 conical surface



(d) Machined roughness Case 2 conical surface



(e) Machined roughness Case 1 groove



(f) Machined roughness Case 2 groove

Fig.9 Machined profiles along the line of the cavity cone with complex geometry

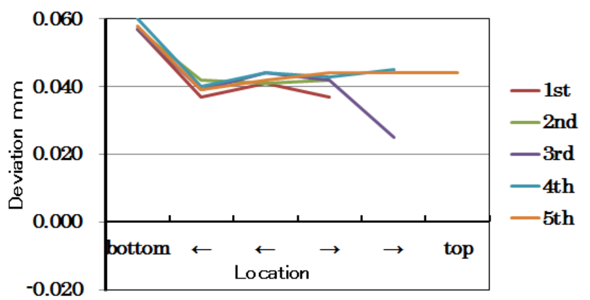
4.2 When machining a truncated cone cavity with groove

Machining time was 1 hour 28 minutes 28 seconds (only tapered part), as shown in Table 9, when a core truncated cavity cone was being machined with grooves (Fig. 1 (b)) using only linear axes. It was 55 minutes 12 seconds (only tapered part) when the same workpiece was being machined using the indexing simultaneous 4-axis control with a rotary axis.

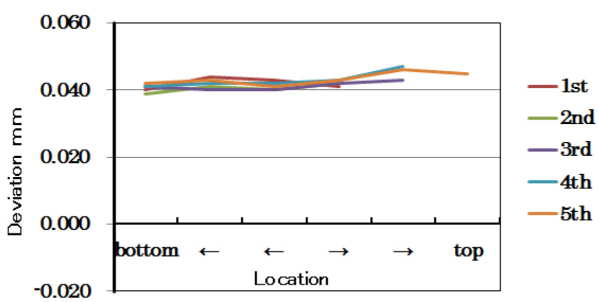
In machining of a core truncated cavity cone with grooves (Fig. 1 (b)), the machining time was shorter by 38% when using a rotary axis, and machining efficiency was enhanced by 1.6 times. Naturally, the enhancement rate of machining efficiency is larger for the following cases: when workpiece material is hard, a vertical wall is long, and an angle of vertical wall is steep because a tool with large L/D ratio is required. Contrarily, it is smaller when workpiece material is soft, a vertical wall is short, and an angle of vertical wall is gradual. The machining conditions when only linear axes were used and when rotary axes with synchronous 4-axis control were used were exactly the same except for differences in the tool L/D ratio and the feedrate. When the workpiece was being machined with the synchronous 4-axis control, the feedrate was as fast as 2,000 mm/min. The difference in machining efficiency was due to the difference in the feedrate. Note that Fig. 9 shows deviation components without considering the influence caused by the angle of a truncated cone cavity.

Table 10 Surface roughness of the bevel gear （Rz μm）

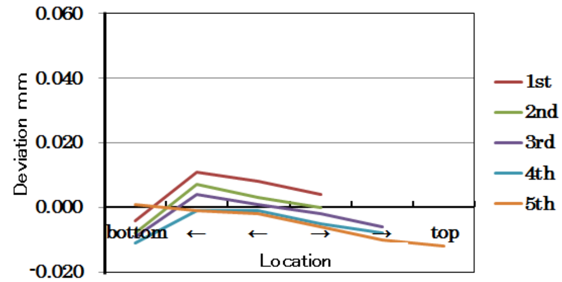
	5 axis machining (pattern 2)		3 axis machining (pattern 1)	
Position	Left gear tooth	Right gear tooth	Left gear tooth	Right gear tooth
Vertical	1.3	1.5	7.8	2.4
Horizontal top	1.7	1.8	6.9	8.3
Horizontal middle	1.7	1.8	8	8.4
Horizontal bottom	1.8	1.9	9.3	8



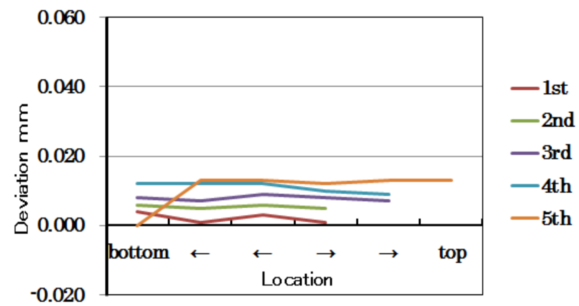
(a)Simultaneous 3-linear axis control machining with ball end mill (Right gear tooth)



(b)Simultaneous 3-linear axis control machining with ball end mill(Left gear tooth)



(c)Rotating motion and simultaneous 2-linear-axis control machining (Right gear tooth)



(d)Rotating motion and simultaneous 2-linear-axis control machining (Left gear tooth)

Fig.10 Distributions of machined deviations of bevel gear

Circularity profiles at three sections and finish profiles at three edges were measured. Fig. 8 and Fig. 9 show the typical examples. Surface roughness, circularity, and straightness obtained from the profiles are compared in Table 9. Surface roughness at the relatively flat part was around 2.6 μmRz—almost the same in both machining methods. Whereas in 3-linear-axis machining, surface roughness at the groove part is 5.9 μmRz—2 times to the flat part. This is because the cutting conditions were too severe for a tool with L/D = 7 so that chatter vibrations were induced while machining the grooves. Surface roughness becomes better under the less severe cutting conditions, which do not induce chatter vibrations, but it drastically decree ses the machining efficiency.

Also, circularity for the part other than grooves differs considerably between two different machining methods. Circularity was 7.9 μm in 3-linear-axis machining, whereas as small as 4.8 μm with an additional rotary axis C. The results were similar for straightness at edges. Straightness was 3 μm or less while machining with only three linear axes, whereas it was as small as 2 μm with an additional rotary axis C.

4.3 Straight bevel gear

4.3.1 Difference of machining efficiency between with ball end mill and square end mill

Machining time calculated by CAM was 4 minutes 56 seconds for machining of one bevel gear groove (Fig. 1 (c))—double edge surface of one groove by an NC program designating the cusp height as 2.6 μm—in 3-linear-axis machining using a ball end mill (pattern 1). Note that the spindle speed was 6000 min-1 and feedrate was 1200 mm/min. The machining time under the same conditions but in 5-axis machining using a square end mill (pattern 2) was 2 minutes 46 seconds (56%). Average feeding pitch was 0.18 mm for the pattern 1 and 0.34 mm for the pattern 2. Mostly, the calculated machining time differs due to the difference of this average feeding pitch.

Actual machining time was 4 minutes 6 seconds for the pattern 2, and it was longer by 48% than the time calculated by CAM. This is because the time for Automatic Tool Changer (ATC) or acceleration/deceleration is not included in the time calculated by CAM.

4.3.2 Difference of machining efficiency due to difference of tool L/D ratio

As mentioned above, 44% of difference exists when different types of tools were used. In the case of machining with a ball end mill, a tool overhang (L/D = 9.5) is big, and the spindle speed and feedrate was suppressed to 40% of the 5-axis machining for the pattern 1, therefore assumed machining time was as long as 12 minutes and 20 seconds.

Test machining was conducted under the same conditions and measured surface roughness for both patterns to seek how low the feedrate should be to suppress chatter vibrations for pattern 1. Thus, it was found that lowering the feedrate by 30% was enough. Then, machining test was conducted at the spindle speed and feedrate lower by 30%. As a result, the actual machining time was 18 minutes 26 seconds which was 4.5 times longer compared to machining with a square end mill and the surface roughness was 4.2 μmRz.

4.3.3 Difference of surface roughness between machining with ball end mill and square end mill

The surface roughness was measured at three points, and the average with a ball end mill was 10.8 μmRz (feedrate 50%) and 4.8 μmRz (feedrate 40%), whereas it was 3.4 μmRz with a square end mill. A square end mill achieved the value very close to an expected, calculated roughness of 2.8 μmRz, but a ball end mill achieved the value far worse than expected and calculated.

4.3.4 Difference of machining accuracy between 3-axis machining and 5-axis machining

Fig. 10 shows machining deviations of bevel gears measured by Coordinate Measuring Machine (CMM) in two machining methods: 3-axis machining (feedrate 30%) and 5-axis machining.

1) While 5-axis machining with a square end mill, machined deviation at the right and left gear teeth is as small as 10 μm. The machining deviation is about 1/5 of 3-axis machining, to be mentioned below, and machined accuracy is considerably good.

2) While 3-axis machining with a ball end mill, machined deviation is the largest at the bottom of right and left gear teeth, and gradually decreases towards the teeth end on the right tooth whereas almost constant on the left tooth. The deviation is 70 to 80 μm at the teeth bottom, which is about 60 μm more than in 5-axis machining. Note that in the case of this bevel gear, about 1 mm from the bottom to end of tooth does not contact between gears, so it can be ignored.

Then the machined deviation except that 1 mm was evaluated, and was within 40 μm to 60 μm on the right teeth with variation of only 20 μm. The machined deviation was as large as 60 μm at the tooth bottom because cutting resistance increased due to interference with a workpiece at the ball end while machining at the tooth bottom with a ball end mill. Also, direction of action is nearly horizontal so that elastic deformation increased. Secondarily, cutting resistance occurs at the tool end which is thin and long protruded, so that the elastic deformation became large.

It is possible to decrease the surface roughness by suppressing chatter vibrations with a lower cutting speed and feedrate. It is assumed the machined deviation would decrease by minimizing the cutting depth (= cutting allowance for finishing) or feedrate per tooth as the cutting resistance would be lower to some extent. In this study, the cutting allowance was 0.1 mm for finishing, which is general for machining of gears, but it seems too severe for comparing such two patterns.

In this study, deterioration of machined accuracy due to tool wear is not in the scope, but deterioration may occur at the ball end in 3D machining with a ball end mill. Whereas, in 5-axis machining with a square end mill, the side edge moves while contacting with a workpiece, so tool wear can be suppressed. Thus, deterioration of machined accuracy is smaller than a ball end mill. However, a square end mill has a limit that concave cannot be machined.

4.4 Relation between complexness of profile and machining time

Table 11 shows the measurement results of machining efficiency and machined accuracy of aforementioned three types of workpieces. For a core truncated cone which has a simple shape, the machining time is almost the same between 3-axis machining and 5-axis machining. Next, for a core truncated cavity cone with grooves, 3-axis machining takes 1.6 times longer than 5-axis machining to achieve almost the same surface roughness and machined accuracy. In other words, even if L/D ratio of a tool is the same, machining efficiency increases by 1.5 times as the freedom of machining method is enhanced. Furthermore, in the case of a complex geometry bevel gear, it took 4.5-times-longer machining time to achieve the same level of results. In other words, a tool L/D ratio = 9.5 in 3-axis machining is improved to = 4.5 in 5-axis machining, and if a tool diameter D is the same, then the character frequency increases by 4.5 times in proportion to $(L/D)^2$. Therefore, the machining efficiency differs due to difference of active stability caused by such as chattering stability.

Thus, it was confirmed that even if the workpiece geometry is more complex, 5-axis machining can drastically reduce the machining time by improving machining phenomena when L/D ratio is the same, or in proportion to $(L/D)^2$ when L/D ratio is different. Also, almost the same level or better machined accuracy was achieved. Thus, it was confirmed that a high-precision 5-axis machining center can outpace the 3-linear-axis machining—which was believed to be advantageous in terms of machined accuracy.

As for a profile that can be machined by a square end mill, it is more advantageous to use a square end mill as both machining efficiency and surface roughness can be improved by several dozen percent to three times.

Table 11 Machining productivity and machined accuracy of various geometrical parts at finishing process

Part geometry	Machine tool	Machining productivity		Machining accuracy		
		Machin-ing time [min]	Ratio	Cylindri-city [μm]	Straightness [μm]	Surface roughness [μmRz]
Core cone	3 axis MC	31	0.98	2.6	2.7	2.6
	5 axis MC	31.5	1	0.6	1.9	1.7
Cavity cone with grooves	3 axis MC	88.5	1.6	7.9	2.8	5.9
	5 axis MC	55.2	1	4.8	3.1	2.6
Straight bevel gear (1groove)	3 axis MC	18.4	4.5	Deviation 40-60		6.5
	5 axis MC	4.1	1	Deviation 10		1.5

The above mentioned results show that when an irregular-shaped workpiece is machined on a 3-axis machining center, there are no choices other than using a ball end mill. Besides, the accessibility to the machining point is bad and machining is performed under lower conditions accordingly, resulting in lower machining efficiency. On the other hand, when machining is performed on a 5-axis machining center, suitable postures of workpieces can be selected depending on what is being machined, which provides better accessibility. In addition, a tool with a smaller L/D can be used, so machining can be performed under hard cutting conditions. These factors work positively to enhance machining efficiency.

5 CONCLUSIONS

Regarding pre-hardened steel workpieces in various profiles, machining efficiency and machined profile error were compared between machining on a table-on-table type 5-axis machining center and on a vertical machining center. The results are as follows:

1) Regarding a simple core truncated cone shown in Fig. 1 (a), surface roughness was around 2.6 μm—almost the same between two machining methods. Circularity and straightness measured in 5-axis machining with a rotary axis were around 3 μm, which was lower than 5 μm of 3-linear-axis machining. It was because the radial rotation-error of the C-axis was smaller than the motion errors of X- and Y-axis while circular interpolation.

2) Regarding a core truncated cavity cone with grooves shown in Fig. 1 (b), which requires a ball end mill with L/D > 7 in 3-linear-axis machining, machining efficiency was enhanced by 1.6 times on a 5-axis machining center than on a vertical machining center. Finished surface roughness was 2.6 μmRz on both machines, but circularity and straightness were much better on a 5-axis machining center as a tool with short protruded part is usable. Note that finishing surface roughness at grooves was as large as 5.9 μmRz in 3-linear-axis machining due to chatter vibrations. It is required to suppress chatter vibrations by loosening the cutting conditions.

3) In finish machining of a straight bevel gear shown in Fig. 1 (c), the machined accuracy of 40 μm and surface roughness of 4.2 μmRz that are similar to ball end mill machining were target. The machining efficiency was 4.5 times in 5-axis machining with a square end mill compared to in 3-axis machining with a ball end mill.

4) It was confirmed that if the workpiece shape is more complex, 5-axis machining can reduce more machining time. Machined accuracy is almost the same level in both patterns. It was confirmed that a high-precision 5-axis machining with consideration of machining phenomena can outpace the 3-linear-axis machining—which was believed to be advantageous in terms of machining accuracy.

REFERENCES

[1] Alves, J.T., Guingand, M. and Vaujany, J.P., Designing and Manufacturing Spiral Bevel Gears Using 5-Axis Computer Numerical Control (CNC) Milling Machines, Journal of Mechanical Design, Vol.135,No.2(2013), 024502, doi:10.1115/1.4023153.

[2] Ibaraki, S., Kakino, Y., Akai, T., Takayama, N., Yamaji I. and Ogawa, K., Identification of Motion Error Sources on Five-axis Machine Tools by Ball-bar Measurements (1st Report): -Classification of Motion Error Components and Development of the Modified Ball Bar Device (DBB5)-, Journal of the Japan Society for Precision Engineering, Vol.63, No.3 (2010), pp.333–337. (in Japanese)

[3] Kakino, Y., Ihara, Y. and Shinohara, A., DBBhou niyoru NC kousakukikai no seidohyoukahou, (1990) Realize Co., High Accuracy CNC Coordinate Measuring Machine STRATO-Apex Series, Catalog No.16001(5) (2013), p.5.

[4] Takayama, N., Ota, H., Ueda, K. and Takeuchi, Y., Study on the Improvement of Motion Accuracy of 5 Axis Control Machining Center : Comparison of Motion Accuracy of Trunnion Type and Table-on-Table Type, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.76, No.772 (2010), pp.3261–3267. (in Japanese)
[5] Takayama, N., Ota, H., Ueda, K. and Takeuchi, Y., Study on the Improvement of Motion Accuracy of 5 Axis Control Machining Center : Influence of the Rotating Axis Travelling Range on the Alignment Error, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.77, No.777 (2011a), pp.2162–2168. (in Japanese)
[6] Takayama, N., Akai, T., Wakizaka, M. and Takeuchi, Y., Study on the Improvement of Motion Accuracy of 5 Axis Control Machining Center : Measurement of Alignment Errors of the Rotating Axis and their Compensations, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.77, No.782 (2011b), pp.3951–3960. (in Japanese)
[7] Tsuji, I., Kawasaki, K., Abe, Y. and Gunbara, H., Manufacturing Method of Large-Sized Spiral Bevel Gears Using Multi-Tasking Machine Tool with Five Axis Control, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol.77, No.775 (2011), pp.728–736. (in Japanese)