Manufacturing Method of Large-Sized Spiral Bevel Gears in Cyclo-Palloid System Using Multi-Axis Control and Multi-Tasking Machine Tool

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Abstract

The large-sized spiral bevel gears in a Klingelnberg cyclo-palloid system are manufactured using multi-axis control and multi-tasking machine tool. This manufacturing method has some advantages such as arbitrarily modification of tooth surface and machining of the part except tooth surface. The pitch circular diameter of the gear treated in this study is more than 1,000 mm. For this study, first the numerical coordinates on the tooth surfaces of the spiral bevel gears are calculated and the tooth profiles are modeled using a 3D-CAD system. Afterwards, the large-sized spiral bevel gears were manufactured based on a CAM process using multi-axis control and multi-tasking machine tool. After rough cutting, the workpiece was heat-treated and it was finished by swarf cutting using a radius end mill. The real tooth surfaces were measured using a coordinate measuring machine and the tooth flank form errors were detected using the measured coordinates. Moreover, the gears were meshed with each other and the tooth contact patterns were investigated. As a result, the validity of this manufacturing method was confirmed.

1. Introduction

The large-sized spiral bevel gears are usually used for power transmission of pulverized coal mill in thermal power generation. Due to the increase of energy demand in the world, the demand of large-sized spiral bevel gears has also increased in recent years and hereafter the demand may increase more and more. The large-sized spiral bevel gears are usually manufactured based on a cyclo-palloid system and have equi-depth teeth as well as face hobbing system [1-3]. The spiral bevel gears in this system are usually generated by a continuous cutting procedure using a special generator which Klingelnberg Co., Ltd. has developed. However, the number of the production of the generator corresponding to the large-sized spiral bevel gears has recently decreased and the production cost has been expensive.

It has been possible to machine the complicated shape because of the development of multi-axis control and multi-tasking machine tool under this condition [4, 5]. Therefore, the high precsion machining of the large-sized spiral bevel gears has been expected.

In this paper, the large-sized spiral bevel gears in the Klingelnberg cyclo-palloid system are manufactured using multi-axis control and multi-tasking machine tool. This manufacturing method has some advantages such as arbitrarily modification of tooth surface and machining of the part except tooth surface. The pitch circular diameter (PCD) of the gear treated in this study is more than 1,000 mm. For this study, first the numerical coordinates on the tooth surfaces of the spiral bevel gears are calculated and the tooth profiles are modeled using a 3D-CAD system. The material of the workpiece was 17CrNiMo06 and it was machined by swarf cutting using a coated carbide end mill. After rough cutting, the workpiece was heat-treated, and it was finished based on a CAM process through the calculated numerical coordinates. The real tooth surfaces were measured using a coordinate measuring machine and the tooth flank form errors were detected using the measured coordinates. As a result, the detected tooth flank form errors were small. Moreover, the tooth contact patterns of the manufactured large-sized spiral bevel gears were observed and those positions were good. From these results, the validity of the manufacturing method using multi-axis control and multi-tasking machine tool was confirmed.

2. Tooth surfaces of spiral bevel gears

The generator and five numbers of starts of cutter heads that Klingelnberg Co., Ltd. manufactures are usually utilized in spiral bevel gear cutting in the cyclo-palloid system. The equi-depth teeth of complementary crown gear are produced one after another by rotating and turning motions of the cutter in this method. That is, the tooth trace of the complementary crown gear is an extended epicycloid. Therefore, the spiral bevel gears in this system are generated by a continuous cutting procedure. In this study, the large-sized spiral bevel gears with the tooth trace of the extended epicycloid are manufactured using multi-axis control and multi-tasking machine tool.

Figure 1 shows the basic concept that produces an extended epicycloid. $\mathrm{O}\text{-}xyz$ is the coordinate system fixed to the crown gear and z axis is the crown gear axis. O_c is the center of both the rolling circle R and the cutter. The cutter fixed to the rolling circle R rotates under the situation. OO_c is the machine distance and is denoted by M_d. When the rolling circle R of radius r (M_d - q) rolls on the base circle Q of radius q, the locus on the pitch surface described

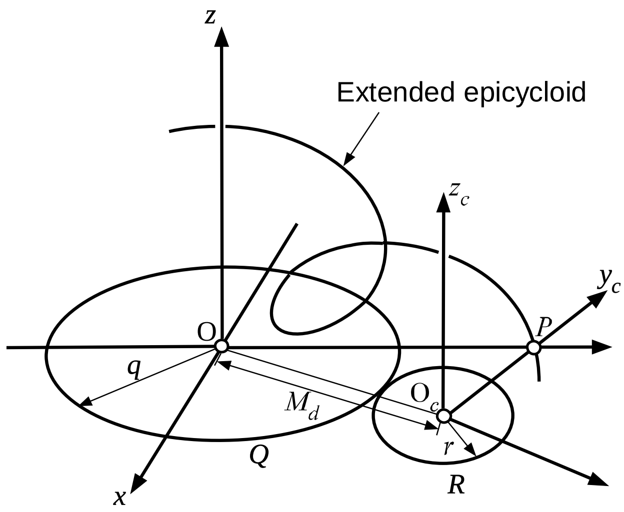

Fig. 1: Extended epicycloid

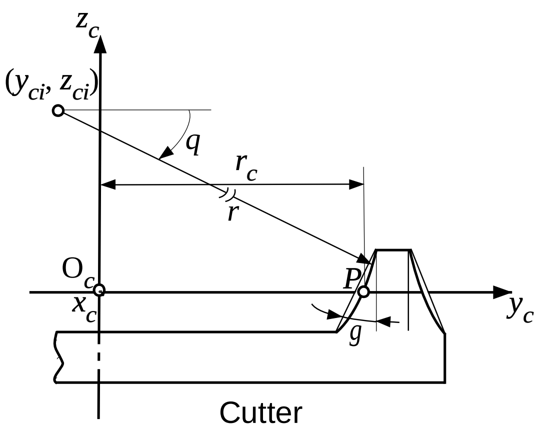

Fig. 2: Cutting edges of cutter

by the point P which is a point fixed to the circle R is an extended epicycloid. When the spiral bevel gear is usually generated for hard cut on the special generator after heat-treatment, the cutter with circular arc cutting edges is used. These circular arc cutting edges provide a profile modification to the tooth surfaces of the generated gear. Therefore, a cutter with circular arc cutting edges is considered in this paper.

Figure 2 shows the cutter with circular cutting edges. O_c-$x_c y_c z_c$ is the coordinate system fixed to the cutter. O_c is the cutter center. z_c is the cutter axis. r_c is the cutter radius. g is the pressure angle of the inner cutting edge of the cutter. r is the radius of the curvature of circular arc cutting edge. (y_{ci}, z_{ci}) is the coordinates of the center of curvature of circular arc in plane x_c=0, and are expressed as a function of g and r [7]. q is the parameter which represents inner curved line. The inner cutting edge $\boldsymbol{X}_c$ is expressed on plane $y_c z_c$ in O_c-$x_c y_c z_c$ by the following equation:

$$\boldsymbol{X}_c(q) = \begin{bmatrix} 0 \\ y_{ci} + r_c \cos q \\ z_{ci} - r_c \sin q \end{bmatrix} \tag{1}$$

The surface of the locus described by $\boldsymbol{X}_c$ in O-xyz is expressed as:

$$\boldsymbol{X}(n, q) = \boldsymbol{C}(q_1)\boldsymbol{X}_c(q) + \boldsymbol{D}(n) \tag{2}$$

where $\boldsymbol{C}$ is the coordinate transformation matrix for the rotation about z axis:

$$\begin{aligned}
\boldsymbol{C}(q_1) &= \begin{bmatrix} \cos q_1 & -\sin q_1 & 0 \\ \sin q_1 & \cos q_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
q_1(n) &= \frac{M_d n}{r} + \Theta_0 \\
\cos \Theta_0 &= \frac{R_m^2 + r_c^2 - M_d^2}{2 R_m r_c} \\
\boldsymbol{D}(n) &= \begin{bmatrix} -M_d \sin(n - q_0) \\ M_d \cos(n - q_0) \\ 0 \end{bmatrix} \\
\cos q_0 &= \frac{M_d^2 + R_m^2 - r_c^2}{2 M_d R_m}
\end{aligned} \tag{3}$$

In Eqs. (2) and (3), n is a parameter which represents the rotation angle of the cutter about z axis and R_m is the mean cone distance as shown in Fig. 3. $\boldsymbol{X}$ expresses the equation of the tooth (tool) surface of the complementary crown gear. The unit normal of $\boldsymbol{X}$ is expressed by $\boldsymbol{N}$.

The complementary crown gear is rotated about z axis by angle y and generates the tooth surface of the spiral bevel gear. We call this rotation angle y of the crown gear the generating angle. When the generating angle is y, $\boldsymbol{X}$ and $\boldsymbol{N}$ are rewritten as $\boldsymbol{X}_y$ and $\boldsymbol{N}_y$ in O-XYZ assuming that the coordinate system O-xyz is rotated about z axis by y in the coordinate system O-XYZ fixed in space. When y is zero, O-XYZ coincides with O-xyz.

Assuming the relative velocity $\boldsymbol{W}(\boldsymbol{X}_y)$ between the crown gear and the generated gear at the moment when generating angle is y, the equation of meshing between the two gears is as follows [8, 9]:

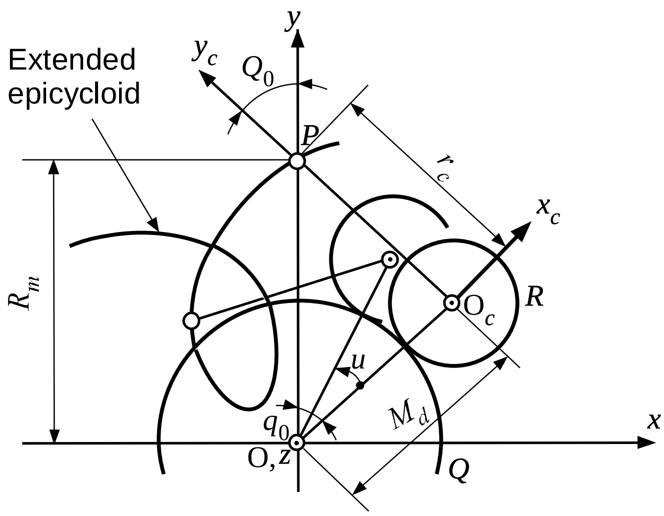

Fig. 3: Locus of cutting edge

$$\boldsymbol{N}_y(n, q; y) \bullet \boldsymbol{W}(n, q; y) = 0 \tag{4}$$

From Eq. (4), we have $q = q(n, y)$. Substituting $q(n, y)$ into $\boldsymbol{X}_y$ and $\boldsymbol{N}_y$, any point on the tool surface of the crown gear and its unit normal are defined by a combination of (n, y), respectively. When the tool surface of the complementary crown gear in O-XYZ is transformed into the coordinate system fixed to the generated gear, the convex tooth surface is expressed. A similar expression is applied to the concave tooth surface. In this case, the difference of the turning radius between inner and outer cutting edges E_{xb} that provides a crowning to the tooth surface of the generated gear should be considered. The convex and convcave tooth surfaces of the gear are expressed as $\boldsymbol{X}_g$ and $\boldsymbol{X}_g'$, respectively. The concave and convex tooth surfaces of the pinion are expressed as $\boldsymbol{X}_p$ and $\boldsymbol{X}_p'$, respectively. Moreover, the unit nomals of $\boldsymbol{X}_g$, $\boldsymbol{X}_g'$ $\boldsymbol{X}_p$, and $\boldsymbol{X}_p'$ are expressed as $\boldsymbol{N}_g$, $\boldsymbol{N}_g'$ $\boldsymbol{N}_p$, and $\boldsymbol{N}_p'$.

3. CAD/CAM system

The numerical coordinates on the tooth surfaces $\boldsymbol{X}_g$, $\boldsymbol{X}_g'$ $\boldsymbol{X}_p$, and $\boldsymbol{X}_p'$ of the spiral bevel gears were calculated based on the concept in the previous section. Moreover, those unit normals $\boldsymbol{N}_g$, $\boldsymbol{N}_g'$ $\boldsymbol{N}_p$, and $\boldsymbol{N}_p'$ were also calculated. Table 1 shows the dimensions of the spiral bevel gears. Table 2 shows the cutter specifications and machine settings in the calculation of the design. PCD of the gear is 1,350 mm.

The determined coordinates are changed by the phase of one pitch after the tooth surfaces $\boldsymbol{X}_g$, $\boldsymbol{X}_g'$ $\boldsymbol{X}_p$, and $\boldsymbol{X}_p'$ are calculated. This process is repeated and produces the numerical coordinates on other convex and concave tooth surfaces. When the range of the

Table 1: Dimensions of spiral bevel gear

	Pinion	Gear
Number of teeth	16	40
Pitch circle diameter	540.0 mm	1,350.0 mm
Pitch cone angle	21.801 deg.	68.199 deg.
Hand of spiral	Right	Left
Normal module	24.9799	
Shaft angle	90 deg.	
Spiral angle	32 deg.	
Pressure angle	20 deg.	
Mean cone distance R_m	727.0 mm	
Face width	185.0 mm	
Whole depth	56.21 mm	

Table 2: Cutter specifications and machine settings

Cutter radius	r_c	450.0 mm
Radius difference	E_{xb}	4.5 mm
Radius of curvature of circular arc	r, (r ')	3,500 mm
Cutter blade module		23.0 mm
Pressure angle		20 deg.
Base circle radius	q	546.9441 mm
Machine distance	M_d	610.4189 mm

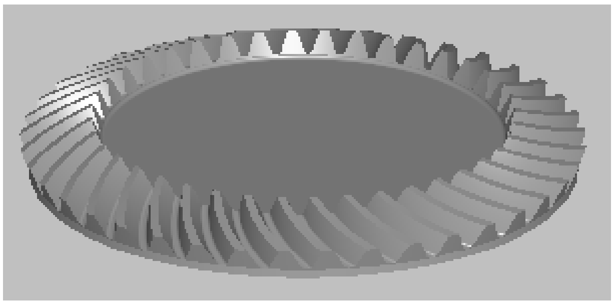

Fig. 4: Tooth profile of gear modeled using 3D-CAD system

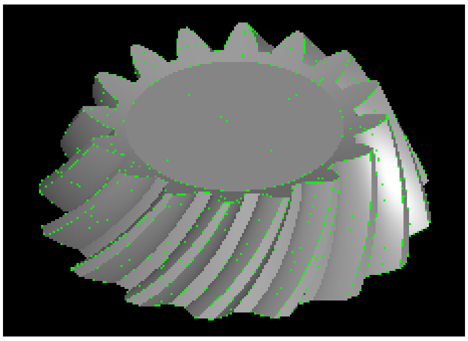

Fig. 5: Tooth profile of pinion modeled using 3D-CAD system

existence of the workpiece that is composed of the root cone, face cone, heel, and toe etc. is indicated, the spiral bevel gear is modeled.

Figures 4 and 5 show the tooth profiles of the gear and pinion modeled using a 3D-CAD system based on the calculated numerical coordinates. The tool pass is calculated automatically after checking tool interferences, choosing a tool, and indicating cutting conditions. Therefore, the CAM process can be realized. When the numerical coordinates of the tooth surfaces are calculated, the tooth surfaces are estimated by the smoothig of a sequence of points, removal of the profile of undercutting, offset of tool radius, and generation of NURBS surface. Moreover, the calculations of intersecting curved lines of convex and concave tooth surfaces, and sectional curved line, the approximation of straight line are cunducted. The approach escape is added in order to avoid the interference. When the attitude of the tool and coordinate transformation are conducted, NC data and IGES (Initial Graphics Exchange Specification) data for the machining and display can be obtained.

4. Manufacturing of large-sized spiral bevel gears

The large-sized spiral bevel gears were manufactured based on CAD/CAM system mentioned above. The manufacturing processes were divided into three parts, namely, roughing, semi-finishing, and finishing in machining.

4.1 Manufacturing of gear

The gear was machined by a ball end mill utilizing a vertical machining center with 3-axis for CNC milling machine on ahead. However, the gear could not be machined efficiently because of the machining using only one point on end mill. This manufacturing mehod was not suitable for the large-sized gear with PCD of more than 1,000 mm. Moreover, the accuracy of machining could not attain our goal. Therefore, a 5-axis control machine (DMG Co., Ltd. DMU210P) was utilized. In this case, the plural surfaces except installation surface can be machined and tool approach from optimal direction can be realized using mult-axis control since the structure of the 2-axis of the inclination and rotation in addition to 3-axis of straight line are added. Therefore, It is possible to use a thicker tool. This means to be expected to reduce the machining time and to obtain better roughness. The radius end mills made out of cemented carbide for a hard cutting tool was used in the machining of tooth surface. The number of edges is twelve, and the diameters of end mills are 20 mm and 10 mm, respectively. The ball end mills were used in the machining of tooth bottom. The number of edges is twelve, and the diameters of end mills are 10 mm and 5 mm, respectively. The gear-work made out of 17CrNiMo06 was prepared. The tool pass was 1 mm for the large-sized gear. First, the gear-work was rough-cut and was heat-treated. Afterward, the gear was semi-finished with the machining allowance of 0.2 mm after heat-treatment. Finally, the gear was finished with the machining allowance of 0.05 mm by swarf cutting that is machined using the side of end mill. The machining with the high acuuracy and high efficiency utilizing the advantage multi-axis control and multi-tasking machine tool in swarf cutting is expected.

Table 3: Conditions of gear machining

Processes	Diameter of end mill (mm)	Revolution of main spindle (rpm)	Feed (mm/min.)	Depth of cut (mm)	Time/one side (min.)
Semi-finishing	20.0	2,000	1,150	0.3	110
Finishing	20.0	2,200	1,100	0.05	310

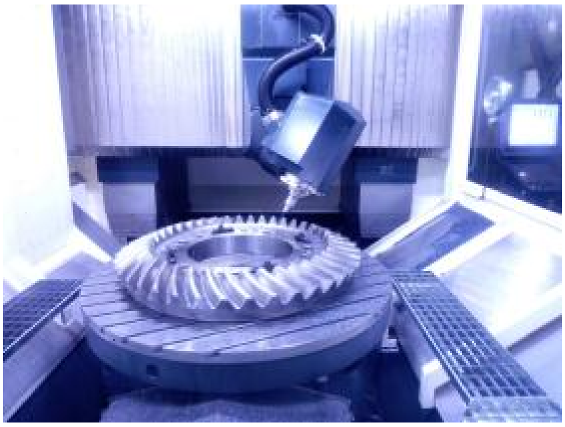

Fig. 6: Gear-work on multi-tasking machine

Fig. 7: Swarf cutting of gear

Table 3 shows the conditions for semi-finishing and finishing in gear machining. Figure 6 shows the gear-work on the multi-axis control and multi-tasking machine and Fig. 7 shows the situation of swarf cutting of the gear. The machining time of one side in rough-cutting is about 6 hours and it in both semi-finishing and finishing is about 7 hours. The machining was finished without trouble such as the defect of the end mill.

4.2 Manufacturing of pinion

A 5-axis control machine (MORI SEIKI Co., Ltd. NT6600) was utilizied in pinion machining. The radius end mills made out of cemented carbide for a hard cutting tool was

Table 4: Conditions of pinion machining

Processes	Diameter of end mill (mm)	Revolution of main spindle (rpm)	Feed (mm/min.)	Depth of cut (mm)	Time/one side (min.)
Semi-finishing	16.0	2,800	1,100	0.2	480
Finishing	16.0	3,300	1,100	0.05	1,440

Fig. 8: Pinion-work on multi-tasking machine

used in the machining of tooth surface. The number of edges is twelve, and the diameters of end mills are 20 mm and 16 mm, respectively. The ball end mills were used in the machining of tooth bottom. The number of edges is twelve, and the diameters of end mills are 10 mm and 5 mm, respectively. The material of the pinion-work is the same as that of the gear-work. The pinion-work was rough-cut and was heat-treated. Then, the pinion was semi-finished with the machining allowance of 0.2 mm after heat-treatment. Moreover, the the pinion was finished with the machining allowance of 0.05 mm by swarf cutting. Table 4 shows the conditions for semi-finishing and finishing in pinion machining. Figure 8 shows the pinion-work on the multi-axis cotrol and multi-tasking machine. The machining time of one side in rough-cutting is about 8 hours and it in both semi-finishing and finishing is about 32 hours. The machining was finished without trouble such as the defect of the end mill.

5. Tooth flank form error and tooth contact pattern

The real gear and pinion tooth surfaces were measured using a coordinate measureing machine and were compared with nominal data using the coordinates and those unit surface normals [10-13]. Sigma M&M 3000 developed by Gleason Works was utilized. This measuring machine corresponds to large-sized spiral bevel gears. Figure 9 shows the measured result of the gear and Fig. 10 shows that of pinion. The tooth flank form errors are not more than about ±0.06 mm and pitch accuracy is 1 class in JIS (Japanese Industrial

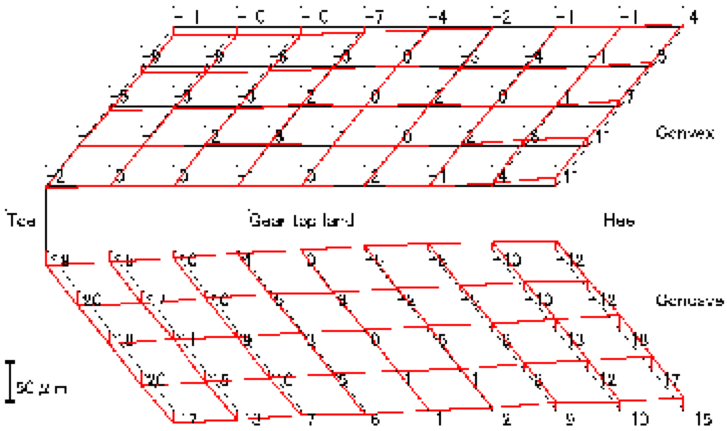

Fig. 9: Measured result of gear (µm)

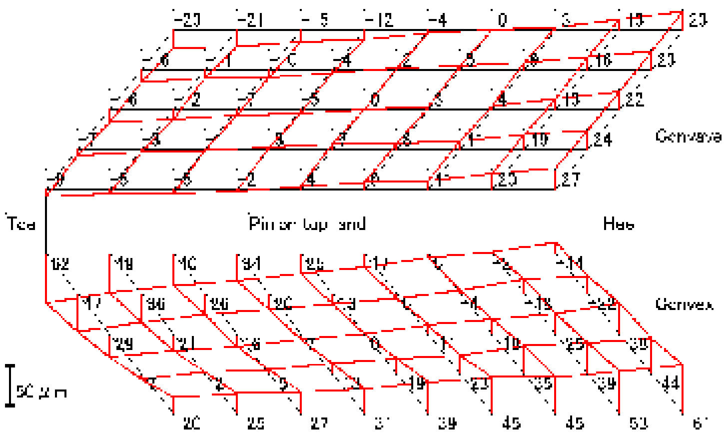

Fig. 10: Measured result of pinion (µm)

Standards) in both the cases of the gear and pinion. We suppose that these errors will not have an influence on the tooth contact patterns for large-sized spiral bevel gears

The large-sized spiral bevel gears were set on a gear meshing tester and the experimental tooth contact patterns were investigated. Figures 11 and 12 show the results of the tooth contact patterns on the gear tooth surfaces of drive and coast sides, respectively. The tooth contact pattern is positioned at the center of tooth surface and its length is about 50 % of tooth length based on the analysis of the tooth contact pattern. The experimental tooth contact patterns are positioned around the center of tooth surfaces of both drive and coast sides, respectively although the length of the tooth contact pattern of drive side is smaller somewhat. From these results, the validity of the manufacturing method using multi-axis control and multi-tasking machine tool was confirmed.

6. Conclusions

Fig. 11: Tooth contact pattern of drive side

Fig. 12: Tooth contact pattern of coast side

The large-sized spiral bevel gears are manufactured based on a cyclo-palloid system and are usually generated by a continuous cutting procedure using a special generator which Klingelnberg Co., Ltd. has developed. However, the number of the production of the generator corresponding to the large-sized spiral bevel gears has recently decreased and the production cost has been expensive.

In this paper, a manufacturing method of large-sized spiral bevel gears in the Klingelnberg cyclo-palloid system using multi-axis control and multi-tasking machine tool was proposed. For this study, first the numerical coordinates on the tooth surfaces of the spiral bevel gears were calculated and the tooth profiles were modeled using a 3D-CAD system. Afterwards, the large-sized spiral bevel gears were manufactured based on a CAM process using multi-axis control and multi-tasking machine tool. After rough cutting, the workpiece was heat-treated and it was finished by swarf cutting using radius end mills. The real tooth surfaces were measured using a coordinate measuring machine and the tooth flank form errors were detected using the measured coordinates. Moreover, the gears were meshed with each other and the tooth contact patterns were investigated. As a result, the validity of this manufacturing method was confirmed.

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