621. 923. 1 : 621. 833. 2

Study on Formate Grinding Method of Constant Depth Tooth Spiral Bevel Gears*

(By No. 0 Cutter and Non-Tilting Cutter Shaft)

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In this report, a cutting and grinding method of constant depth tooth spiral bevel gears is described, i.e. the gear is formed by the Gleason's No. 0 cutter or grinding wheel having an equal pressure angle on inner and outer blades and the pinion is generated by the No. 0 cutter or grinding wheel whose shaft is not tilted to the rotor axis.

In generating the pinion, the pinion blank and the rotor are rotated at the rate of the number of teeth of the pinion to that of the crown gear and at the same time the pinion blank is driven away from the rotor and moreover approached to it.

By this method, although it is an approximate one, a good available tooth bearing with a crowning and a profile modification can be obtained on one trial of grinding by the No. 0 wheel only, consequently a mass and small quantity grinding production system of bevel pairs could be achieved.

1. Preface

In the cutting process of spiral bevel gears and hypoid gears, the method by which the gear is formed and the pinion is generated so as to engage with this gear is universally used by reason of advantages for mass production, but a grinding process of this method is not yet performed. The intermittent grinding method⁽¹⁾ made the formate-grinding of the gear very easy without the fear of wearing the grinding wheel and burning the gear tooth surface which could be finished to very good roughness. It is a problem how to grind the pinion so as to mesh with this gear.

Originally, in order to manufacture the pinion so as to mesh with the formed gear, the cutter or grinding wheel shaft must be tilted to the rotor (the cradle) shaft theoretically. But, in order to tilt the grinding wheel shaft, the structure of the rotor in the grinder is very complicated and the designing and manufacturing of this part are very difficult, so that both shafts of the grinding wheel and the rotor are parallel on all medium and large type grinders at present. If the pinion can be ground without tilting the grinding wheel shaft, the grinding mass production of spiral bevel and hypoid gears will

become possible because the gear can be formate-ground easily by the intermittent grinding method. Further, if both the pinion and the gear can be manufactured by the Gleason's No. 0 grinding wheel only whose inner and outer pressure angles are equal, it is very advantageous because it can be applied in the small quantity production. In this report, the above mentioned grinding method is described about a constant depth tooth spiral bevel gear.

2. Theoretical cutting method

2.1 Cutting method of the gear

In the plan of Fig. 1, the pinion and the gear axis intersect perpendicularly each other and are parallel to the paper plane. When the plane that is perpendicular to the paper plane of the plan at the pitch line OP is the paper plane of the elevation, in the elevation the gear is on the opposite side of the paper plane and the pinion is on this side and the cutter axis is perpendicular to the paper plane at the point O_c.

To formate the gear, the No. 0 cutter (both inner and outer pressure angles are α_n) whose blade thickness is equal to the normal space thickness of the gear S_n is infed in the direction of tooth depth and both the concave and the convex tooth surfaces are cut at once. After one tooth space is cut, the cutter is returned, the gear blank is indexed by one pitch and the cutter is infed to the next tooth space.

* Received 31 st March, 1969.

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This process is repeated by the number of teeth times. If the No. 0 grinding wheel having the same contour as the cutter is used instead of the cutter, the gear can be ground by the same process. In this case, because the grinding wheel surface contacts closely with the gear tooth surface, the tooth surface is apt to be heated and burn, so that it is very difficult to grind normally. But, as mentioned in the preface, by using the intermittent grinding method it becomes easy.

z_1 and z_2 are the number of teeth of the pinion and the gear, δ_1 and δ_2 are the pitch angles, R_m is the mean cone distance, β is the mean spiral angle and $O_cP=r_c$ is the mean cutter radius. The gear blank is fixed on the cutting machine by setting it on the angle δ_2 to OP and the position of the cutter axis O_c can be set in the distance of $OO_c=r_s$ from O and in the normal distance $O_cE=V$ from OP. V and r_s can be calculated by the next equations.

$$r_s^2 = R_m^2 + r_c^2 - 2R_mr_c \sin \beta \quad \dots\dots\dots(1)$$

$$V = r_c \cos \beta \quad \dots\dots\dots(2)$$

2.2 Cutting method of the pinion

The tooth surface of the gear cut by the above mentioned method is a cone whose axis is the same as the cutter and whose generating line is the cutting edge. In Fig. 1, if the No. 0 cutter for the

pinion whose outer cutting edge coincides closely with the inner one of the cutter for the gear is rotated about its own axis O_c and simultaneously is revolved round the gear axis, the motion of this cutting edge is the same as that of one convex tooth surface of the gear which revolves round the gear axis. (In this case, the rotor axis of the cutting machine coincides with this gear axis). If the pinion blank is set perpendicular to this rotor axis and both the rotor and the pinion blank are rotated with the generating rolling motion so that the ratio of the rotating speed of the pinion blank to the above mentioned revolving speed of the rotor can be $z_1 : z_2$, one concave tooth surface of the pinion can be cut to mesh exactly with the convex tooth surface of the gear because the cutting edge which presents the motion of the convex tooth surface of the gear cuts off a region interfering the mesh with the convex tooth surface of the gear from the pinion blank. By indexing successively, all teeth are cut one by one.

By the same process, the convex tooth surface of the pinion can be cut to mesh with the concave tooth surface of the gear by using the cutter whose inner cutting edge coincides with the outer one of the cutter for the gear. Also, the pinion can be ground by using the grinding wheel instead of the cutter similarly to the case of the gear. (Notice: In the case of both the gear and the pinion, the difference of grinding from cutting is only the use of the grinding wheel instead of the cutter, and the mechanism for cutting is the same as for grinding, so that the process for cutting is the same as for grinding and the cutter axis is the same as the grinding wheel axis. Consequently, in the following states, these terms are randomly used case by case.)

This is the theoretical normal method for cutting the pinion, but in this case the cutter axis must be tilted to the rotor axis by the angle $90^\circ - \delta_2$. As mentioned in the preface, it will be convenient if the pinion can be cut by the No. 0 cutter without tilting the cutter axis, and this method will be described next. Because the pinion is cut without tilting the cutter axis in spite of the theory that the cutter axis must be tilted, the method to be mentioned next is an approximate one, therefore it is the purpose of this report to obtain an available tooth bearing on the ground pairs.

3. Generating speed ratio for cutting pinions

In Fig. 1, OO' that is parallel to the cutter axis is the actual rotor axis of the cutting machine. The pinion blank and the actual rotor are revolved around each other with the ratio of $z_1 : z_2$ (the number of teeth of the crown gear). This is the same case of

Fig. 1 Diagram showing the relation between the cutter, the gear blank and the rotor

both the pinion and the gear being generated and the setting method on the cutting or grinding machine is easy^{(1) (2)}.

$$z_c = \sqrt{z_1^2 + z_2^2} \quad (3)$$

4. Generation of the tooth profile

In the following, it will be assumed that the pinion is left hand spiral and the convex tooth surface of the gear meshes with the concave tooth surface of the pinion, but the next formulas can also be applied in the other cases by considering plus or minus of the symbols.

4.1 Tooth profile of the gear

In Fig. 1 (refer to the side view), S_s is the transverse blade thickness of the cutter for the gear (which is equal to the transverse space thickness of the gear) and α_s is the transverse pressure angle at the mean face width. The transverse pressure angle of the convex tooth surface of the gear is represented by $\alpha_s - \phi_2$, and α_s , ϕ_2 can be calculated by the next formulas. In Fig. 2, β_i is the spiral angle, $O_c P_i = r_{ci}$ is the cutter radius and $O_2 P = R_{v2}$ is the back cone distance at the point P_i on the mean face width of the convex tooth surface of the gear,

$$S_s = S_n / \cos \beta, \quad \phi_2 = S_s / 2R_{v2} \quad (4)$$

$$r_{ci} = r_c - \frac{S_n}{2} \quad (5)$$

$$\sin \beta_i = \frac{R_m^2 + r_{ci}^2 - r_s^2}{2R_m r_{ci}} \quad (6)$$

$$\tan \alpha_s = \frac{\tan \alpha_n}{\cos \beta_i} \quad (7)$$

At a position of an optional cone distance R , the transverse pressure angle of the convex tooth surface of the gear is $\alpha_{sr} - \phi_{2r}$; α_{sr} is the transverse pressure angle of the cutter at this position and ϕ_{2r} is the angle corresponding to ϕ_2 mentioned above. In Fig. 2, β_r and β_{ir} are spiral angles, R_{v2r} is the back cone distance of the gear, $\angle POO_c = \mu$, $\angle P_r O_c$

The gear is on the opposite side of the paper plane and the cutter is on this side. Point P is the center of the tooth space of the gear.

Fig. 2 Detail of the elevation of Fig. 1

$= \lambda$ and $\angle POP_r = \theta_r$ at the point P_r and P_{ir} of the position of R ,

$$\sin \beta_r = \frac{1}{2Rr_c} \{R^2 + R_m(2r_c \sin \beta - R_m)\}$$

$$\sin \beta_{ir} = \frac{1}{2Rr_{ci}} \{R^2 + R_m(2r_{ci} \sin \beta_i - R_m)\}$$

$$\tan \alpha_{sr} = \frac{\tan \alpha_n}{\cos \beta_{ir}}$$

$$\sin \mu = r_c \cos \beta / r_s$$

$$\sin \lambda = r_c \cos \beta_r / r_s$$

$$\theta_r = \mu - \lambda$$

$$\phi_{2r} = \left(R \sin \theta_r + \frac{S_n}{2 \cos \beta_r} \right) / R_{v2r}$$

4.2 Generating the tooth profile of the pinion

Figure 3 is an enlarged diagram of the side view of Fig. 1, namely it shows the meshing condition of equivalent spur gears. In Fig. 3, the position at which the gear tooth is a_1 is equivalent to the position shown in Fig. 1 and a_1 has an angle α_s to $O_1 P O_2$. The gear tooth a is at the pitch point P and has an angle $\alpha_s - \phi_2$ to $O_1 P O_2$. The pinion blank and the rotor are revolved at the ratio of the number of teeth of the pinion to that of the crown gear as mentioned above, so that we consider the meshing of equivalent spur gears that have an involute tooth profile. Now, the gear tooth a_1 is at the position P_2' on its pitch circle and P' and P_1' are the points at which PP_2' , PP' and PP_1' are equal on the pitch line of the crown gear and the pitch circle of the pinion. The line of action PA_1 is perpendicular to a at the point P and $P'A_1$ is perpendicular to PA_1 , so that the tooth profile c_1 of the pinion at the point P_1' is tangent to $P'A_1$ at the point A_1 . In order to

Fig. 3 Meshing condition of equivalent spur gears

mesh the gear tooth with the pinion tooth at this position, the hatched area enclosed by a_1 and c_1 must be cut off from the tooth profile of the pinion. The transverse pressure angle of the No. 0 cutter whose normal pressure angle is α_n is α_s , its cutting edge is b at the pitch point P and is b_1 at the point P' and both b and b_1 are parallel to a_1 . So, if the pinion blank is driven away from the rotor by the gap ε_1 between a_1 and b_1 in parallel with O_1P , the above required area can be cut off from c_1 by the cutting edge b_1 .

Next, we consider the case that the gear rotates by an angle ϕ_2' from the pitch point P and the gear tooth is a_2 at the position P_2'' and the pinion tooth is c_2 at the position P_1'' . In these positions, $PP_2'' = PP_1'' = PP'$, $P'A_2 \perp PA_1$ and c_2 is tangent to $P'A_2$ at A_2 , so that the hatched area between a_2 and c_2 must be cut off. For this purpose, a_2 and c_2 are rotated together about O_1 till a_2 becomes parallel to the cutting edge b . This rotating angle is $(\phi_2' - \phi_2)$ and a_2 , P_2'' , c_2 and P_1'' come to a_2' , P_2''' , c_2' and P_1''' respectively as shown by broken lines. In this instant, the cutting edge is b_2 at the point P''' at which PP_1''' and PP_2''' are equal and b_2 is parallel to a_2' . Therefore, the pinion blank has only to approach the rotor by the gap ε between a_2' and b_2 when the pinion tooth is at the position c_2' .

One method is that the revolving speed of the rotor is changed so that the cutting edge b_2 and b_1 come respectively to the position a_2' and a_1 as the generating goes on, but in this method the mechanism is very complicated⁽³⁾⁽⁴⁾. Thus, in this study the pinion blank is driven away from the rotor and approached to it as mentioned above. As mentioned later about the pair which is used for this experiment and has the number of teeth of 12:36, this mechanism can be reconstructed and applied easily on the cutting and grinding generator which was produced trially in Kyushu University and was used in this experiment.

The next equations show the values of ε and θ_c' by which the rotor must revolve when the pinion rotates by the angle $\angle PO_1P_1''' = \phi_1' + (\phi_2' - \phi_2)$. In Fig. 3, h_k and α_{sa} are the addendum and the transverse pressure angle respectively at the point A_2 and R_{v1} is the back cone distance of the pinion at the point P ,

$$R_{v1} \cos(\alpha_s - \phi_2) = (R_{v1} + h_k) \cos \alpha_{sa} \quad (8)$$

$$\phi_1' = \angle PO_1P_1'' = \tan \alpha_{sa} - \tan(\alpha_s - \phi_2) \quad (9)$$

$$R_{v1} \phi_1' = R_{v2} \phi_2' \quad (10)$$

$$\tan \angle PO_1P_2'' = \frac{R_{v2} \sin \phi_2'}{R_{v1} + R_{v2}(1 - \cos \phi_2')}$$

$$O_1P_2'' = O_1P_2''' = \frac{R_{v1} + R_{v2}(1 - \cos \phi_2')}{\cos \angle PO_1P_2''}$$

$$\angle PO_1P_2''' = \angle PO_1P_2'' + \phi_2' - \phi_2$$

$$\begin{aligned} PE &= O_1P_2''' \sin \angle PO_1P_2''' \\ &\quad - (R_{v1} - O_1P_2''' \cos \angle PO_1P_2''') \tan \alpha_s \\ PP''' &= PP_1''' = R_{v1}(\phi_1' + \phi_2' - \phi_2) \\ \varepsilon &= \frac{PP''' - PE}{\tan \alpha_s} \quad (11) \end{aligned}$$

$$\theta_c' = \frac{R_{v1}}{R_m} (\phi_1' + \phi_2' - \phi_2) = (\phi_1' + \phi_2' - \phi_2) \tan \delta_1 \quad (12)$$

In the position of the cone distance R , these values can be calculated using the values of R_{v1} , R_{v2} , α_s , etc. at the position of R instead of R_{v1} , R_{v2} , α_s , etc. of the above equations and R instead of R_m . These values of ε and θ_c' are calculated at various positions of h_k by giving it various values.

5. Effect of the tooth trace spiral

In Fig. 4, Fig. 2 is redrawn for explaining the cutting method of the pinion and the pinion blank is on this side of the paper plane and the rotor is on the opposite side. When they are revolving in the arrow direction, the tooth profile of the pinion is generated from the tip of the toe to the root of the heel on its concave tooth surface because the tooth trace is spiral. Therefore, the generating motion at the position of the cone distance R takes place later by the angle $\angle P_i, OP_i = \theta_r'$ than that of the mean point P_i . When the motion of the point P_i is taken as the basis of the generating revolution, the revolving angle θ_c of the rotor at each generating position of the tooth profile is presented as the next equation.

$$\theta_c = \theta_c' - \theta_r' \quad (13)$$

θ_c' is the value calculated by Eq. (12) at the position of the cone distance R , and when the tooth profile at the position of the cone distance R is cut at the position of the angle θ_c' from OP , the mean point P_i is at the position of the angle θ_c from OP . And, θ_r' is zero and θ_c is θ_c' at the mean point.

The pinion blank is on this side of the paper plane and the grinding wheel is on the opposite side.

Fig. 4. Difference caused by tooth trace spiral

Moreover, θ_c also means the revolving angle of the grinding wheel center O_c .

In this case, θ_c and θ_c' are positive clockwise from the line OP in Fig. 4 and θ_r' can be calculated by the next equation.

$$\theta_r' = (\phi_{2r} - \phi_2) \tan \delta_2$$

6. Pair used in this experiment

In this experiment, a pair is used whose number of teeth is 12:36, the gear ratio 3, the module 5, the spiral angle $\beta=35^\circ$ left hand and the normal pressure angle $\alpha_n=20^\circ$. Its terms and main values calculated by the above equations are shown in Table 1 and the dimensions of the cutter and the grinding wheel used in this experiment are shown in Fig. 5. Figure 6 shows the relations between θ_c and ϵ about the meshing between the convex tooth surface of the gear and the concave one of the pinion in case of cutting the above-mentioned pair. The curve A shows the values at the toe (cone distance $R=66.868$ mm), B at the position of a quarter face width from the toe ($R=73.868$ mm), C at the mean cone distance ($R_m=80.868$ mm), D at the position of a quarter face width from the heel ($R=87.868$ mm) and E at the heel ($R=94.868$ mm). θ_c is positive clockwise from OP in Fig. 4 and the generating motion revolves counter-clockwise, so that in Fig. 6 the generating motion goes on as the arrow points from right to left and begins at the tip of the toe and finishes at the root of the heel. ϵ is positive in the direction that the pinion blank approaches the rotor i.e. the cutting depth increases towards the

Table 1 Gears used in this experiment

	Pinion	Gear
Number of teeth	12	36
Gear ratio	3	
Module (at heel)	5	
Mean spiral angle	$\beta=35^\circ$ (left)	$\beta=35^\circ$ (right)
Pitch angle	$\delta_1=18^\circ 26'$	$\delta_2=71^\circ 34'$
Pressure angle	$\alpha_n=20^\circ$	
Addendum mm	4.94	2.06
Dedendum mm	3.29	6.17
Whole depth mm	8.23	
Face width mm	28	
Pitch circle diameter at heel mm	60	180
Mean cone distance mm	$R_m=80.868$	

Cutter diameter $2r_c=7.5$ inch=190.5 mm

Normal space thickness of the gear $S_n=6.69$ mm

$r_s=82.316$ mm, $z_c=37.9473$

$\beta_1=33^\circ 32'$ (Convex tooth surface of the gear, concave one of the pinion)

$\alpha_t=23^\circ 35'$ $\alpha_t-\phi_2=22^\circ 37'$

Gear blank material: S 45 C.

tooth depth. The point P_t in Fig. 6 is the position which is corresponding to the point P_1' in Fig. 3 at the mean face width (the gear tooth a_1 is parallel to the cutting edge b_1). a_0 is the position at which the pitch point of the toe is cut, and b_0 , c_0 , d_0 and e_0 are the positions at which each pitch point is cut respectively. The points where the line 3 which is parallel to the longitudinal axis at a_0 intersects the curve B and C show the simultaneously contacting position between the tooth surface and the grinding wheel surface; from this fact it is understood that the neighborhood of the tip at the mean face width and the pitch point of the toe are cut simultaneously. Figure 7 shows the simultaneously contacting lines drawn by properly connecting these intersecting points, corresponding to 1, 2, 3... in Fig. 6, and the generating motion goes on in this order.

Fig. 5 Dimensions of the cutter and the grinding wheel

Fig. 6 Values of infeed to rotating angles of the rotor

As stated above, the pinion blank must be brought close to and then driven away from the rotor as the generating motion goes on. For this purpose, the saddle on which the blank is fixed is driven along the curve F in Fig. 6. Namely, the curve F shows the motion of the blank towards the rotor axis (this F curve represents the actual measurement). Because ϵ is positive in the direction that the blank approaches the rotor, the cutting depth is greater in the beginning of the generating motion and it decreases gradually as the generating motion goes on, the blank is driven farthest at the point P_i in Fig. 6 from the rotor and moreover is brought gradually close to the rotor as the generating motion goes on. Namely, the blank is reciprocated once towards the rotor axis along the F curve while one tooth is generated. The regions above the F curve, which are the neighborhood of the tip and the portion near the root concerning the C curve and thirdly the neighborhood of the pitch point b_0 concerning the B curve, are insufficient in the cutting depth, so that the ground tooth surface is protruded in these regions. These protuberances are shown in Fig. 7 with the inclined lines. The widths of these inclined lines are drawn nearly corresponding to the distance between the C, B, etc. curve and the F curve i.e. the amount of protuberance. From this figure, it is expected that a tooth bearing of the ground surface is within the region surrounded by the broken lines. It comes near the toe and relieves at the heel. As a matter of fact, the tooth bearing can be improved because the auxiliary grinding i.e. the profile modification⁽¹⁾ or the crowning is very easy. In the case of meshing between the convex tooth surface of a pinion and the concave one of a gear, the tooth bearing moves towards the heel and relieves at the toe, which is contrary to the case in Fig. 7.

7. Experiment and results of grinding

The cutter used for cutting the gear is the No. 0 cutter whose diameter is 7.5 inch, whose point width is 2.0 mm and whose blade thickness is made S_n by changing the thickness of its blade panels. The gear is indexed by a simple device which is set on the master worm shaft of the cutting and grinding generator which was produced trially in Kyushu

Fig. 7 Protuberances of the concave tooth surface of the pinion

University, and is infed by the method of reciprocating the saddle by a cam. Both the indexing device and the cam are driven by hand.

The pinion is roughened by the No. 0 cutter whose diameter is 7.5 inch and whose point width is 1.5 mm and the convex and the concave tooth surfaces are finished separately by the No. 0 cutters whose diameter is adjustable and which are separately used for the convex and the concave tooth surfaces. The grinding wheels are also separately used for the convex and the concave tooth surfaces. The grinding wheel is made of Almo H (WA, single crystal) 60 JmV, the coolant is Noritakecut, and the roughness of the finished tooth surfaces is within R_{max} 1μ . On the mechanism for reciprocating the blank towards the rotor axis, there is a method of driving the saddle by a cam, but in this experiment a crank mechanism was used by which the lead screw for driving the saddle was rotated and reversed. This is due to the fact that the cutting and grinding generator can easily be reconstructed. (Because a gear train has already been set up to the lead screw of the saddle in order to generate a hypoid pair by driving the rotor in screw motion⁽⁵⁾). In this case, the motion of the saddle is apt to be instable when the lead screw changes from rotating to reversing, but to avoid it, the author designed the mechanism in stout build and nearly removed the backlash of the lead screw by making its double nuts compete with each other and so on.

The diameter of the cutter and the grinding wheel must be exactly measured and be made equal to the appointed value. For this purpose, a diameter measuring device shown in Fig. 8 was made. This is a modified vernier caliper. When the appointed diameter of the cutter is $2r_{ci}$ and the dedendum of the gear is h_f , we get :

$$d = 2(r_{ci} - h_f \tan \alpha_n) \\ = a + b + e$$

By measuring values of a and b on a universal measuring microscope, e can be calculated. A block-gauge whose length is e is sandwiched between A and B, E is fixed by a set screw and the cutter diameter is adjusted so as to touch closely its cutting

Fig. 8 Diameter measuring device

edge at C and D. By this method the cutter or grinding wheel diameter can be made to an accuracy ± 0.01 mm with a little training. And reversely, the cutter diameter can be known by measuring e . In the case of measuring the inner blade diameter, E is used reversely as shown by broken lines and the distance between F and G is measured by a micrometer. If c is measured previously, the diameter can be known and is adjustable in the same way as stated above because a is used in common.

A tooth bearing of the concave tooth surface of the pinion which was ground by the above mentioned method is shown in Fig. 9. It resembles Fig. 7 very much.

8. Experiment and results of auxiliary grindings

The above mentioned method is in the case that the cutter radii for cutting the gear and the pinion are equal i.e. the crowning is zero. Also, the profile modification is not done. In this case, a one-sided tooth bearing is apt to result from a little error in setting and mounting. In the case of the convex tooth surface of the gear and the concave one of the pinion, the tooth bearing is apt to approach the toe because it is a figure which relieves at the heel as shown in Fig. 7. So, an auxiliary grinding test was carried out by changing the cutter radius for the pinion to that for the gear so as to be crowned. The cutter or the grinding wheel which was used for cutting the pinion is No. 0 whose mean diameter is 7.5 inch (radius=95.25 mm), whose pressure angle is 20° , whose point width is 1.5 mm, and whose dimensions are shown in Fig. 10. Figure 11 shows the tooth bearing on both the convex and the concave tooth surfaces of the pinion finished by this grinding wheel only. On the concave tooth surface of the pinion the tooth profile is modified so as to relieve about 15 microns at the tip and the root, but on the convex one it is not modified. A value ΔT of the crowning which was calculated by next equation⁽⁶⁾ is 0.085 mm at the toe and the heel.

The pinion is ground and the gear is cut. Both the profile modification and the crowning are not done.
Fig. 9 Tooth bearing of the pinion

$$\Delta T = \frac{1}{8} \left(\frac{b}{r_c \cos \beta} \right)^2 \Delta r$$

where r_c is the mean cutter radius, β is the spiral angle, b is the face width, Δr is the difference between the inner and outer cutter radii, $\Delta r = 97.20 - 91.91 = 5.29$ mm.

Figure 11 shows a sufficient available tooth bearing. This was obtained by initial grinding and no trial grindings were done to correct the tooth bearings.

Besides the auxiliary grinding methods such as the profile modification and the crowning, other methods by which a tooth bearing is corrected can be easily applied to this generator; for example, a method by which the heel of the convex tooth surface is ground excessively by resetting the grinding wheel shaft from O_c to O'_c by the angle $\Delta\beta$ as shown in Fig. 12

Fig. 10 Dimensions of the No. 0 cutter and grinding wheel used for finishing the pinion

The profile of the concave tooth surface of the pinion is modified (15μ). Amount of crowning is 0.085 mm

Fig. 11 Tooth bearing after auxiliary grinding

Fig. 12 Correction of a spiral angle

and the tooth bearing is shifted towards the toe of the convex tooth surface, another method by which the grinding wheel is trued so as to change its pressure angle and the tooth bearing is adjusted in the direction of the tooth depth, etc.

But, in this experiment the tooth bearing could be obtained by initial grinding as shown in Fig. 11, so that these correcting grinding methods were not tried. Because the method in this study is an approximate one and there are also some effects of manufacturing errors, the correction grinding methods may be applied if they are needed, and one or two of these trials are sufficient for the purpose, judging from the above mentioned results.

9. Conclusions

1. The pinion which meshes with the formed gear can be manufactured without tilting the grinding wheel shaft and the mass grinding production of constant depth tooth spiral bevel gears is possible.

2. If the amount of crowning is not designated, both the convex and the concave tooth surfaces of the pinion can be manufactured by one No. 0 cutter or a grinding wheel only as mentioned in chapter 8.

This No. 0 cutter can be used also for cutting the gear by a method in which its point width is changed, and both the pinion and the gear can be manufactured by this No. 0 cutter only, so that this method is very useful for the small quantity production. In the case of grinding, wears of the grinding wheel become large by the truing by which the point

width of the grinding wheel is changed, but this can be saved by adjusting the revolving radius of the grinding wheel shaft in the intermittent grinding method, so that both the gear and the pinion can be ground with one No. 0 grinding wheel only by the intermittent grinding method and this method is available for the small quantity grinding production.

3. If the tooth trace is crowned and the tooth profile is modified, an effective tooth bearing can be obtained by grinding once; and although this method is an approximate one, trial grindings are scarcely needed, but sometimes it may be necessary to grind once or twice for correction.

Acknowledgement

This experiment was performed at the Manufacturing Laboratory in Kyushu University. Author expresses his hearty appreciation to Professor Dr. T. Ueno, Mr. T. Yamada and others in the laboratory who helped him in this study.

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