Investigation about Prevention of Tooth Profile Change of Nylon Gears*

(3rd Report; Wear and Tooth Profile Change in Profile
Shifted Nylon Gear.)

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Two prevention methods are proposed in the previous report as the prevention methods of tooth profile change in the course of operation of a nylon gear which transmits the power. And their effect is confirmed by experiments. In this report as a method simpler than those methods, a plus profile shifting of nylon gear is proposed. In the plus profile shifted gear, the tooth thickness of tooth flank increases and the tooth is less liable to deflect. Meanwhile the sliding of tooth is large. In this report the abrasion of tooth of nylon gear is investigated under several profile modification coefficients and this method is examined to see how useful it is as the prevention method of tooth profile change.

Key Words : Machine Element, Tribology, Lubrication, Wear, Gear, Plastic Gear, Nylon Gear, Tooth Profile.

1. Introduction

A tooth of nylon gear (plastic gear) is largely deflected when the tooth is loaded, because its mechanical strength is small. A tooth profile (pressure angle) largely changes, compared with a theoretical tooth profile.⁽¹⁾ Therefore a rotation lag occurs at a mating gear (steel gear). When the next tooth is meshed at the beginning, the edge of addendum of steel gear scoops out the tooth flank of nylon gear, and its characteristic and strength drop.⁽²⁾ For prevention of scoop out of the tooth flank, the following methods were proposed. The tooth profile of mating steel gear was modified by the amount of deflection of tooth of nylon gear in the 1st report.⁽³⁾ In the 2nd report,⁽⁴⁾ a steel stiffener was included in the core of nylon gear tooth (that gear was called SN-gear) and the tooth deflection was reduced.

Both methods effected the prevention in tooth profile change of nylon gear. But in the profile modification of steel gear, the amount of modification depended on the operational condition of nylon gear. And SN-gear had a demerit that its weight was large.

In this report, in view of the fact that the tooth profile change in nylon gear was caused by a large deflection of the tooth, it was tried to make the tooth was less liable to deflect by plus profile shifting of nylon gear. When the tooth profile of the gear is shifted to plus, the tooth thickness of tooth increases over that of a standard gear, which has the same number of teeth. Then the tooth becomes less liable to deflect. But there is a demerit that a sliding of tooth increases when the tooth profile is shifted to plus.

As the plus shifted gear has a merit and a demerit, in this report several operation tests of profile shifted nylon gear were performed to investigate states of abrasion and tooth profile change. The plus profile shift was examined to see how effective is the method for the prevention of tooth profile change.

2. Main Characteristic of Experimental Plus Profile Shifted Gear.

Table 1 shows main specifications of gears used in this experiment. The face width of a nylon gear (MC nylon)⁽⁵⁾ and a steel gear (S45C) was 20 mm and both gears looked like circle plates, whose thickness was equal to the face width. In this table the nylon gear has a number of teeth, i.e. 34. The addendum modification coefficient X of nylon gear is variable from 0.2 to 1.4 in steps of 0.3 as shown in Table 2. Figure 1 shows photographs of the part of tooth in each type profile shifted nylon gear. The center distance increases over the theoretical value as shown in Table 2 because of backlash needed in each gear, i.e. 0.55 mm. In

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Table 1 Specifications of test gears.

	Driving gear	Driven gear
Module	5	
Standard pressure angle	20°	
Number of teeth	34	64
Addendum modification coefficient	by Table 2	0
Diameter of standard pitch circle	170	320
Clearance coefficient	0.25	
Center distance	by Table 2	
Teeth finishing	Hobbing	
Accuracy	JIS B1702 Grade 4~5	

N.B.) A unit of module and diameter of standard pitch circle is mm.

this case the tooth surface roughness in the direction of tooth profile of mating steel gear is the ten points average roughness $R_z=4\sim5\text{ }\mu\text{m}$ of JIS B 0601.

2.1 Deflection of tooth

Values of the deflection of tooth in the nylon gear, which meshed with the steel gear, were calculated by the expression⁽⁶⁾ of Terashima, which was applied by the deflection calculating method of Weber-Banaschek. In this case as the deflection of tooth of profile shifted gear was not included in the expression of Tarashima, a tooth profile approximate curve was expressed by an exponential function whose exponential number was 2 in type (B) and type (C), 1.5 in type (D) and type (E), and 1.25 in type (F). Figure 2 shows comparison of the tooth profile curve with the tooth profile approximate curve in type (C) and type (F) of nylon gear. In this figure type (C) shows an extreme example that the tooth profile curve did not correspond with the tooth profile approximate curve, and type (F) shows an extreme example that the tooth profile curve corresponded with the tooth profile approximate curve (point M; this point is 2 module from the tip of tooth in the direction of radius) in 5 kinds of profile shifted nylon gears in this experiment. Figure 3 shows calculated deflection values of tooth in the direction of a line of action when the normal load 368.5 N (37.6 kgf) acts at the least favourable point in each type nylon gear (modulus of longitudinal elasticity of nylon $E=2.744\text{ GPa}$ (280 kgf/mm²)). The deflection of tooth decreases with an increasing addendum modification coefficient. But this decreased amount of deflection is not large compared with the expected amount.

2.2 Contact ratio

When one gear was plus profile shifted in a pair of gears, the contact ratio decreased. In the nylon gear of this experiment, the contact ratio of type (F)

Table 2 Addendum modification coefficient.

Item	Type	[A]	[B]	[C]
Addendum modification coefficient		0	0.2	0.5
Center distance (mm)		245.00	245.99	247.41
Diameter of intermeshing pitch circle (mm)		170.00	170.69	171.67
Item	Type	[D]	[E]	[F]
Addendum modification coefficient		0.8	1.1	1.4
Center distance (mm)		248.79	250.12	251.42
Diameter of intermeshing pitch circle (mm)		172.63	173.55	174.45

Fig. 1 Tooth profile of profile shifted nylon gears.

Fig. 2 Tooth profile approximate curve.

gear decreased below that of type (A) gear by 0.25, as shown in Fig. 4.

2.3 Sliding velocity of tooth

The sliding velocity of tooth is different at each position of the meshed tooth. Figure 5 shows an example of calculating the average sliding velocity

Fig. 3 Examples of calculated tooth deflection.

Fig. 4 Addendum modification coefficient and contact ratio.

Fig. 5 Average sliding velocity of tooth.

V_a ($V_a = (\omega_1 + \omega_2) \cdot (e_1^2 + e_2^2) / 2e$, ω_1 , ω_2 ; angular velocity of driving and driven gear, e_1 , e_2 ; length of action of approach and recess, e ; length of action) in each type tooth profile at 675 rpm. With an increasing addendum modification coefficient, V_a increases and this value in type (F) gear is 1.43 times as large as that in type (A) gear. Figure 6 shows a specific sliding at the starting point of action, where the tip of tooth of steel gear is pressed largely.

3. Operation Test

3.1 Experimental (test) conditions

The experiment was performed as follows. The number of rotations was 675 rpm at the driving side (in this case the circumferential speed at the pitch circle of type (A) gear was 12 m/s). The torques at the driving side were 14.7 N·m (1.5 kgf·m) and 29.4 N·m (3 kgf·m). All the experiments were performed under no lubrication.

3.2 Gear testing rig

In this experiment the power circulating gear testing rig, whose center distance could be varied from 190 mm to 300 mm, (5) was used.

3.3 Measuring items and measurement

In this experiment the abrasion of nylon gear, the change of tooth profile and the temperature of tooth were measured. The measuring method was the same as in the earlier report. (1)~(4) The measuring position of tooth temperature of nylon gear is shown in Fig. 7.

4. Experimental Results and Discussion

4.1 Wear of nylon gear

Figure 8 shows the progress state of wear in each nylon gear in the course of operation. On the ordinate of this figure the wear is indicated by the average thickness (depth) of wear of tooth $[g/(z \cdot$

Fig. 6 Specific sliding at starting point of action.

Fig. 7 Measured position of tooth temperature.

$\rho \cdot b \cdot l)$, where g ; wear mass of each nylon gear, z ; number of teeth of nylon gear, ρ ; density of nylon material, b ; face width, l ; length of tooth profile as shown in Fig. 9.]

From Fig. 8 the following may be known.

In Fig.(a), whose torque was 14.7 N·m, the wear was the smallest when the addendum modification coefficient was between 0.2 and 0.5, except at the start of operation (the total number of rotations $N_T = 10^5$). With the other addendum modification coefficient, the larger the coefficient, the greater was the wear. This tendency of wear is similar to the tendency of average sliding velocity of tooth in Fig. 5. Because the sliding velocity changed according to the difference of addendum modification coefficient and in consequence the wear changed, an abnormal wear did not occur at the tooth flank of

Fig. 8 Wear of nylon gear in the course of operation.

nylon gear on account of the small deflection of tooth under the small torque. Therefore when the torque is small, the plus profile shift is not needed, and when the tooth profile is plus shifted, the sliding velocity of tooth becomes large and the wear increases.

When an abnormal wear, which occurred at the tooth flank, grew large, it could be recognized even at the dimension of the photograph of Fig. 10. This will be confirmed by the tooth profile record diagram of Fig. 13. (The photograph of Fig. 10 shows the tooth surface of each nylon gear at $N_T=10^7$, when the experiment finished. As the abnormal wear did not occur, the white line like a belt did not appear as shown in the photograph of Fig. 12.)

Fig. 8(b), in which the torque was large, shows the same tendency as Fig. 8(a) up to $N_T=3 \times 10^6$. But when N_T exceeded 6×10^6 and the operation time was long, there was no difference in wear thickness between gears, whose addendum modification coefficient was larger than 0.5. The reason is that when the addendum modification coefficient was small, the sliding velocity of tooth became small, the wear became small but the deflection of tooth was larger than that of gear whose addendum modification coefficient was large. Thus the abnormal wear of tooth flank became large.

Because the wear of type (A) and type (B) gears, whose sliding velocity of tooth was small, became larger than that of type (C) ~ type (F) gears, the abnormal wear, which occurred at the side of tooth flank, grew large. This may be seen from the tooth profile record diagram of Fig. 11

Fig. 9 Length of tooth profile.

Fig. 10 Tooth surface without abnormal wear (torque 14.7 N·m).

and the photograph of Fig. 12.

From the above results of wear, when the sliding velocity was large and gears were operated under a large torque for a long time, there was a merit when the tooth profile of nylon gear shifted to plus and the deflection of tooth was small.

4.2 Tooth profile change of nylon gear

Figure 11 shows the tooth profile change in each nylon gear in the course of operation when the torque is 29.4 N·m. In each figure, a line of $N_T=0$ shows a tooth profile record diagram before operation. A tooth profile record diagram for each total number of rotations is drawn at intervals of the quantity of wear from the diagram of $N_T=0$. Therefore an interval in each tooth profile diagram indicates the wear thickness (depth) of tooth.

As shown in the earlier report⁽¹⁾, the tooth profile of the power transmitting nylon gear, which meshed with the steel gear, largely changed from the starting point of action to the pitch point and changed a little from the pitch point to the tip of tooth in the course of operation, as in the case of the type (A) gear.

The reason that the tooth profile changes, is as follows. The tooth of nylon gear deflects when the tooth of steel gear meshes with that of nylon gear. Then the rotation of the steel gear drops

Fig. 11 Tooth profile change of profile shifted nylon gears in the course of operation.

Fig. 12 Tooth surface with abnormal wear (torque 29.4 N·m).

and the tip of tooth of steel gear scoops out⁽⁷⁾ the tooth flank of nylon gear when the next tooth of nylon gear begins to mesh with the next tooth of steel gear. This is an abnormal wear. The abnormal wear decreases as shown in Fig. 11 when the addendum modification coefficient is large. With an increased addendum modification coefficient, the wear thickness of tooth becomes uniform and the error (tooth profile error) is made small.

Figure 12 shows photographs of tooth surface of nylon gears of Fig. 11. The abnormal wear occurs at the white line of tooth flank. In these photographs, the amount of the abnormal wear of each gear can not be compared correctly, but in the type (A) gear, whose tooth profile largely

changes, the white line is wider than that of other gears. Figure 13 shows an example of tooth profile change of nylon gear in the course of operation when the torque is 14.7 N·m. As gears are operated under a small torque, the tooth profile changes a little. Comparing type (A) gear with type (F) gear, a difference in the tooth profile change due to the various addendum modification coefficients can not be recognized.

In the profile of each nylon gear as shown in Fig. 11, the position of the abnormal wear is established as shown in Fig. 14. Measuring the area of this position, Fig. 15 is obtained. This figure is similar to the relation between the addendum modification coefficient and the

Fig. 13 Tooth profile change of profile shifted nylon gear, which was operated under small torque.

Fig. 14 Position regarded as abnormal wear.

Fig. 15 Addendum modification coefficient and area of abnormal wear.

deflection of tooth in Fig. 3 and that between the addendum modification coefficient and the specific sliding at the starting point of action in Fig. 6. The tendency of the abnormal wear is similar to that of the deflection and that of the specific sliding of the starting point of action, because the deflection of tooth decreases as the addendum modification coefficient (addendum modification coefficient of +(plus)) becomes large, and because the specific sliding at the starting point of action decreases due to the intermeshing pitch circle being moved to the side of addendum. When the addendum modification coefficient is increased, the deflection of tooth decreases and the abnormal wear decreases because the tooth stops a rolling contact when the tip of tooth of the steel gear meshes with the tooth of nylon gear.

4.3 Tooth temperature

Figure 16 shows the tooth temperature of each profile shifted nylon gear. The

Fig. 16 Tooth temperature of profile shifted nylon gear.

lower limit temperature in each gear is an average room temperature in the experiment. The upper limit temperature is a balance temperature of tooth. Therefore the temperature rise in tooth comes between the upper limit temperature and the lower limit temperature. Comparing with Fig. 5, the tendency of the temperature rise of tooth in Fig. 16 is similar to that of the average sliding velocity of tooth.

5. Conclusions

The tooth profile of the nylon gear was shifted to plus for the purpose to prevent a tooth profile change in nylon gear in the course of operation. This effect was examined by an experiment with the following results.

- (1) When the addendum modification coefficient was large, the sliding velocity of tooth (the average sliding velocity of tooth) became large. The wear of the nylon gear was larger than that of the gear with small addendum modification coefficient (the addendum modification of the gear was 0.2 or under) in the beginning of operation, but in the long time operation, it became smaller than that of the gear with small one.
- (2) When the addendum modification coefficient was large, the tooth profile of nylon gear did not largely change in the long time operation.
- (3) When the addendum modification coefficient was large, the deflection became small and the intermeshing pitch circle came close to the starting point of action. Therefore the abnormal wear, which occurred at the nylon gear, decreased.
- (4) The relationship between the addendum modification coefficient and the temperature of tooth of nylon gear was similar to that between the addendum modification coefficient and the sliding velocity of tooth (the average sliding velocity of tooth).

(p.s.)

When the tooth of the nylon gear was shifted to plus, the life of gear

Fig. 17 Comparison of cracks.

increased. For example, when the type (A) gear and the (E) gear were operated under torque 44.1 N·m (4.5 kgf·m) and number of rotations 675 rpm, a crack occurred in the type (A) gear under $N_T=8.5 \times 10^6$ as shown in Fig. 17(a). But in type (E) gear a crack occurred only under $N_T=10^7$ as shown in Fig. 17(b).

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