Investigation about the Prevention of Tooth Profile Change of Plastic Gears

(1st Report; Amount of Profile Modification of Steel Gear,
which Meshed with Nylon Gear)*

By Naohisa TSUKAMOTO** and Jiasun SHI***

As a prevention method of tooth profile change of a nylon gear, which meshes with a steel gear, this paper proposes a profile modification of steel gear. And a reasonable amount of modification is obtained by experiments. From the results, it is clear that the expression of the amount of profile modification $\Delta\alpha$ (minutes) of steel gear is as follows.

$$\Delta\alpha = \zeta(T_c \cdot T / 9.8b) + \xi$$

ζ : Change value of pressure angle change (minutes)/(N·m/m)·s, T_c : Contact period of teeth of nylon gear (second), T : Torque acting on nylon gear (N·m), b : Face width (m), ξ : Basic value of pressure angle change (minutes).

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

1. Real State of Tooth Profile Change of Nylon Gear and Problems Involved

Nylon gears (plastic gears) have many advantages, such as low weight, low vibration and low noise. But there is a drawback that the tooth profile changes largely in the directions of face width and whole depth in the course of operation.

In the direction of face width the center of face width of nylon gear swells and the tooth changes like a cask as stated in the earlier report⁽¹⁾. This phenomenon occurs because the temperature varies in each position of face width as the heat radiation varies in each position of face width. When the tooth profile changes, the gear tooth contact force is large at the large swollen position in the center of face width (this position is a large swollen position.) And at this position a crack occurs often. This tooth profile change can be prevented when the tooth of nylon gear has a counter-crowning and this effect is already confirmed⁽¹⁾ in terms of the experiment. Therefore the problem of the tooth profile change in the direction of face width of nylon gear has been solved.

On the other hand the tooth profile of nylon gear in the direction of whole depth changes as shown in Fig.1. In this figure, this tooth profile record diagram was measured using the basic circle plate type tooth profile measuring apparatus. The distance of each line indicates a abrasional thickness in the course of operation. In this figure, the abrasion increases from the starting point of action K toward the pitch point P and decreases from the P point to the tip of tooth T_i. Therefore the pressure angle of tooth changes largely. This indicates a typical tooth profile change in the direction of tooth depth with the power transmission nylon gear (driving nylon gear), which meshes with the steel gear. This phenomenon occurs when the tip of tooth of steel gear scoops out⁽²⁾ the tooth flank of nylon gear because the tooth of nylon gear, which meshes

Fig.1 Tooth profile change in the direction of whole depth of nylon gear, which meshes with steel gear.

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** Lecturer, Department of Mechanical Engineering, Chiba Institute of Technology, (2-17-1, Tsudanuma, Narashino, Chiba, Japan.)

*** Engineer, Bao-ji Fork-Lift Manufacture Shop, (Bao-ji City, San-xi, P.R. China.)

Table 1 Specifications of test gears

	Type I		Type II		Type III	
	Driving gear	Driven gear	Driving gear	Driven gear	Driving gear	Driven gear
Module	3		4.5		5	
Standard pressure angle	20°		20°		20°	
Number of teeth	30	60	25	35	17	37
Addendum modification coefficient	0	0	0	0	0	0
Diameter of standard pitch circle	90	180	112.5	157.5	85	185
Clearance coefficient	0.25		0.25		0.25	
Face width	10	10	10	10	10	10
Center distance	135		135		135	
Teeth finishing	Hobbing		Hobbing		Hobbing	
Accuracy	JIS B 1702 Grade 4~5*					

N.B.) Driving gear is made of MC nylon⁽¹⁾ and driven gear is made of S45C.
A unit of module, diameter of standard pitch circle, face width and center distance is mm.

* single pitch error 18~32μm
tooth profile error 18~32μm
runout 51~90μm

with the steel gear, deflects largely when the tooth of nylon gear begins to mesh with the tooth of steel gear.

Fig.2 shows the change of pressure angle at the tip of tooth in three specifications of nylon gear in the course of operation. The vertical axis in this figure indicates the change of pressure angle, as compared with the pressure angle before operation. This pressure angle is a reference. The value of minus(-) denotes the case when the pressure angle decreases from that before operation. $T_c \cdot (T/b)$ of the horizontal axis indicates the acting amount of torque in the required time. (2)(3) [T_c : the contact period of tooth of nylon gear (2)(3)(s), T : torque acting on the nylon gear, b : face width (m)] In Fig.2, the experimental values are discontinuous, but the change of pressure angle correlates with $T_c \cdot (T/b)$ as the real line in each figure shows. When the value of $T_c \cdot (T/b)$ is large, the change of pressure angle is large. Because when the value of $T_c \cdot (T/b)$ is large, the power (torque) in the tooth of nylon gear acts for a long time. And the tooth deflects largely. The tip of tooth of steel gear scoops out the tooth flank of nylon gear. The change of incline of real line in the figure is large from the start of operation to $N_T = 1.5 \times 10^6$, and small there after. Therefore the tooth profile (the pressure angle) in the direction of tooth depth of nylon gear almost changes up to near $N_T = 1.5 \times 10^6$. Fig.3 shows the change of ξ and ζ in the course of operation. The basic value ξ (min.) of pressure angle change is one at the point of intersection of real line in Fig.2 and the change value ζ of the pressure angle change is expressed by the incline. The change amount of tooth profile of nylon gear (the change amount of pressure angle in the tip of tooth) $\Delta\alpha$ (min.) in the course of operation from this figure is calculated by the next expression.

$$\Delta\alpha = \zeta(T_c \cdot T / 0.98b) + \xi \dots (1)$$

Fig.2 Pressure angle change in the course of operation of nylon gear, which meshes with steel gear of no profile modification.

Fig.3 ξ and ζ values of pressure angle of nylon gear, which meshes with steel gear of no profile modification.

Fig.4 Nylon gear whose core of tooth and body were made of steel.

2. Prevention Method of Profile Change of Nylon Gear

The above scheme illustrates the prevention method of tooth profile change in the direction of tooth depth of nylon gear, which changes like Fig.1.

① Method to modify the tooth profile of mating steel gear. This method is as follows. The tooth face of mating steel gear is modified by the amount of deflection of tooth of nylon gear. And the tooth profile change of nylon gear is prevented by preventing the tip of tooth of steel gear from scooping out the tooth flank of nylon gear.

② Method(4) to make smaller the pressure angle of nylon gear as compared with the standard pressure angle. When the gear teeth are cut, the pressure angle of nylon gear is smaller than that of mating steel gear. In this case, it is likely that the pressure angle becomes large when the tooth of nylon gear is forced and the tooth deflects(2) largely with the tooth flank as the starting point. When the tooth of nylon gear deflects, both pressure angles are same.

③ Method to make the tooth of nylon gear difficult to deflect. For example, the method is as follows. When the core of tooth of nylon gear and a section of gear body are made of steel in Fig.4, the tooth of nylon gear is difficult to deflect and the tooth profile change is prevented.

In this investigation the above-mentioned several prevention methods were confirmed by an experiment to see how effective is the method for the prevention of tooth profile change in the direction of tooth depth of nylon gear, whose tooth profile changed following the expression (1). And from the experimental results the most effective prevention method of tooth profile change of nylon gear was found. Under the investigation arrangement, the amount of profile modification of meshed mating steel gear will be examined under several operational conditions in this report and a reasonable amount will be determined.

Table 2 Experimental conditions

Type I gears			
Number of rotations s^{-1} (rpm)	8.3 (500)	16.6 (1000)	25.0 (1500)
Torque N·m(kgf·m)	17.64(1.8) 12.74(1.3)	I-A-1 I-B-1	I-A-2 - I-A-3 I-B-3
Type II gears			
Number of rotations s^{-1} (rpm)	23.52(2.4) 15.68(1.6)	II-A-1 II-B-1	II-A-2 - II-A-3 II-B-3
Type III gears			
Number of rotations s^{-1} (rpm)	17.64(1.8) 12.74(1.3)	III-A-1 III-B-1	III-A-2 - III-A-3 III-B-3

Fig.5 Profile modification of steel gear.

3. Operation Test of Nylon Gear, which Meshes with Profile Modified Steel Gear

3.1 Experimental (test) conditions and test gears

The experiment was performed as follows. The gears were used with same specifications as the gears in Table 1. (The accuracy of steel gear is grade 3 of JIS B 1702) and the torques and the number of rotations used are as shown in Table 2. Fig.5 shows the method of profile modification of steel gear in this experiment. The value of s was $40 \mu m$ in each type gear. That is to say, in this experiment the steel gear was modified suitably and the suitable operation condition was investigated in this gear. The value of u was $(\epsilon - 1) \cdot t_e$ (ϵ : contact ratio, t_e : normal pitch) in each type gear. The profile modification of steel gear was done by the teeth grinding machine. In this case the tooth surface roughness in the direction of tooth depth of each steel gear was from 3.0 to 3.5 μm in ten points average roughness(R_z) of JIS B 0601.

Table 3 Experimental results

Experimental symbols	Abrasive mass of nylon gear mg	Total number of rotations	Damage of tooth of nylon gear
I-A-1	277.2	10^7	None
I-A-2	265.6	10^7	None
I-A-3	242.6	10^7	None
I-B-1	164.7	10^7	None
I-B-3	144.5	10^7	None
II-A-1	294.2	3×10^6	Crack
II-A-2	300.8	6×10^6	Crack
II-A-3	287.4	6×10^6	Crack
II-B-1	388.3	10^7	None
II-B-3	309.6	10^7	None
III-A-1	265.1	10^7	None
III-A-2	242.4	10^7	None
III-A-3	220.6	10^7	None
III-B-1	162.7	10^7	None
III-B-3	147.5	10^7	None

3.2 Gear testing rig

In this experiment the power circulating gear testing rig, whose center distance is 135 mm, was used. In this experiment as the gear noise was to be measured, the test gears and the gear box were covered separately from other parts, the same as in the earlier report.⁽⁵⁾

3.3 Measuring items and measurement

In this experiment the abrasion of nylon gear, the change of tooth profile, the temperature of tooth and noise of gear were measured. The measuring method was the same as in the earlier report.⁽¹⁾ ~⁽⁵⁾

4. Experimental Results and Discussion

4.1 Abrasion of nylon gear

Table 3 shows the abrasion mass at the end of experiment of nylon gear, which meshed with the profile modified steel gear, and the position of breakage of tooth. In this experiment all the nylon gears, except II-A gears, could be operated with no breakage up to the total number of rotations, $N_T = 10^7$ as shown in Table 3. In II-A gears the torque was large. When type I and type III nylon gears meshed with the non-profile modified steel gear, these gears could not operate⁽⁶⁾ with no breakage up to $N_T = 10^7$ at 500 rpm and 14.7 N·m (1.5 kgf·m). Therefore if the tooth profile of meshed mating steel was modified, the life of nylon gear would lengthen. (The difference in cracked state of nylon gear was not recognized with profile modification of steel gear.)

The abrasion of a nylon gear, which meshed with the profile modified steel gear, was less than that of one, which meshed with the non-profile modified steel gear. Fig.6(a) shows the abrasional mass of nylon gear in the course of operation of experiment III-A group. Fig.6(b) shows the abrasional mass of nylon gear, which meshed with the non-profile modified steel gear and the experimental conditions of this experiment were the same as those of the experiment III-A group. For example, comparing III-A-1 and III-A-1' at $N_T =$

Fig.6 Comparison of the abrasion of nylon gear in terms of profile modification or not of steel gear.

3×10^6 , the abrasional mass of the former is half that of the latter.

When the tooth profile of steel gear was modified, the abrasion of nylon gear decreased. Because when the nylon gear meshed with the profile modified steel gear, the abrasion from K point to P point, which dominated the amount of abrasion of nylon gear, decreased. If the abrasion is uniform on the tooth profile, the abrasion of nylon gear will decrease and its life will lengthen.

There is other feature that there is no difference in the abrasion of nylon gear due to the difference in the number of rotations (rpm). In Fig.6(b) the abrasion is large in the order of 500, 1000 and 1500 rpm (III-A-1', III-A-2' and III-A-3'). There is a difference in abrasion due to the difference of the number of rotations clearly. But in Fig.(a) there is no difference of abrasion due to the difference in the number of rotations in spite of the order of abrasion being the same as in Fig.(b) (at $N_T = 10^7$).

Next Fig.7 shows all of the results of this experiment in terms of the relation between the specific abrasion weight of nylon gear and $T_c \cdot (T/b)$. When the abrasion of nylon gear is substituted by an amount of a specific abrasion of nylon gear [abrasion mass mg/(steel gear equivalent Hertzian stress N/m^2)(N.B.)(2)(3)(5)/ number of teeth/face width m/gross rotational frequency], the solid line in this figure denotes the experimental results of earlier report⁽⁶⁾ and the abrasion of nylon gear, which meshed with the steel gear of non-modified tooth profile. From this figure the amount of specific abrasion of nylon gear, which meshed with the profile modified steel gear, is found small. Especially the effect appears clear when the gears operate over a value of $T_c \cdot (T/b)$ which is close to 4 ($N \cdot m/m$)·s and for a long time. That

Fig.7 Comparison of the amount of specific abrasion of nylon gear in terms of profile modification or not of steel gear.

is to say, there is an effect of the profile modification of steel gear when the steel gear drives the nylon gear whose number of teeth is small, at a low speed and a large torque.

In this investigation, the amount of profile modification of steel gear is 40 μm in each type gear. In the experiment performed under several operational conditions, the amounts of profile modification were not reasonable for $T_c \cdot (T/b)$. Therefore as in Fig.7 the experimental results do not always relate to $T_c \cdot (T/b)$. Table 4 shows the reasonable amount of profile modification $\Delta\alpha$ of steel gear in the experimental conditions, which were calculated by the expression (1). (Symbol of -(minus) before the numerical value implies that the value is subtracted from the pressure angle 20° .)

4.2 Tooth profile change of nylon gear

Fig.8 shows an example of tooth profile change in the course of operation of nylon gear, which meshed with the steel gear with no modification of tooth profile. This figure shows the results when the experiment was performed under the same conditions as III-A group of Fig.8(b). As the tooth profile of steel gear was not modified, the change was the same as in Fig.1.

When the nylon gear meshed with the profile modified steel gear, the abrasion between K and P was small, compared with Fig.(a) up to $N_T=6 \times 10^5$. Therefore the change of pressure angle was small too. But in III-A-1 and III-A-2, the abrasion

Table 4 Amount of profile modification of steel gear, as calculated by expression (1)

Experimental symbols	$\Delta\alpha$ min. (μm)					
	10^5	6×10^5	1.5×10^6	3×10^6	6×10^6	10^7
I-A-1	-13.56 (21.9)	-24.69 (39.8)	-30.38 (50.0)	-34.68 (55.9)	-38.99 (62.9)	-42.16 (68.0)
I-A-2	-9.78 (15.8)	-18.46 (29.8)	-22.89 (36.9)	-26.25 (42.3)	-29.61 (47.8)	-32.08 (51.7)
I-A-3	-8.52 (13.7)	-16.38 (26.4)	-20.40 (32.9)	-23.44 (37.8)	-26.48 (42.7)	-28.72 (46.3)
I-B-1	-11.46 (18.5)	-21.23 (34.2)	-26.22 (42.3)	-30.00 (48.4)	-33.78 (54.5)	-36.56 (59.0)
I-B-3	-7.82 (12.6)	-15.23 (24.6)	-19.01 (30.7)	-21.88 (35.3)	-24.74 (39.9)	-26.85 (43.3)
II-A-1	-18.10 (42.0)	-32.16 (74.6)	-39.36 (91.3)	-44.80 (104.4)	-50.24 (116.6)	-54.26 (125.9)
II-A-2	-12.05 (28.0)	-22.20 (51.5)	-27.38 (63.5)	-31.31 (72.7)	-35.24 (81.8)	-38.13 (88.5)
II-A-3	-10.03 (23.3)	-18.87 (43.8)	-23.39 (54.3)	-26.81 (62.2)	-30.23 (70.2)	-32.75 (76.0)
II-B-1	-14.06 (32.6)	-25.52 (59.2)	-31.38 (72.8)	-35.81 (83.1)	-40.24 (93.4)	-43.50 (101.0)
II-B-3	-8.69 (20.2)	-16.66 (38.7)	-20.73 (48.1)	-23.81 (55.3)	-26.90 (62.4)	-29.17 (67.7)
III-A-1	-19.34 (48.6)	-34.22 (86.0)	-41.83 (105.1)	-47.58 (119.5)	-53.34 (134.0)	-57.58 (144.6)
III-A-2	-12.67 (31.8)	-23.22 (58.3)	-28.62 (71.9)	-32.70 (82.1)	-36.78 (92.4)	-39.79 (100.0)
III-A-3	-10.45 (26.2)	-19.56 (49.1)	-24.21 (60.8)	-27.74 (69.7)	-31.26 (78.5)	-33.86 (85.1)
III-B-1	-15.64 (39.3)	-28.11 (70.6)	-34.49 (86.6)	-39.31 (98.7)	-44.14 (110.9)	-47.69 (119.8)
III-B-3	-9.21 (23.1)	-17.52 (44.0)	-21.77 (54.7)	-24.98 (62.7)	-28.20 (70.8)	-30.56 (76.8)

between K and P increased and the tooth profile changed from $N_T=1.5 \times 10^6$, as in the nylon gear, which meshed with the steel

Fig.8 Comparison of the tooth profile change of nylon gear in terms of profile modification or not of steel gear.

gear having non-modified tooth profile in Fig.(a). These things increased and changed remarkably in a long time operation. The tooth profile changed at $NT=10^7$ in III-A-3, in which the value of $T_c \cdot (T/b)$ was small. This phenomenon occurred when the amount of profile modification of steel gear $40 \mu m$ was much smaller than for value of $\Delta\alpha$ in Table 4. If the amount of profile modification of steel gear was closed to the value of $\Delta\alpha$ in Table 4, the abrasion between K and P was not large especially in a long time operation like Fig.9. Therefore the tooth profile change was small. That is to say, $\Delta\alpha$ of expression (1) denotes a reasonable value of profile modification of steel gear. If this value is s of Fig. 5, the tooth profile change (the pressure angle change) of nylon gear will be prevented.

The tooth profile changes of III-A group and I-B-3 were investigated in the above. Fig.10 shows all the pressure angle changes (the pressure angle change in the tip of tooth) in the course of operation of nylon gear in this experiment. In this figure, one of the pressure angles of nylon gear is smaller than 20° , because the amount of profile modification of steel gear is small in the operational condition $T_c \cdot (T/b)$.

Fig.9 Tooth profile change of nylon gear, which meshes with steel gear whose teeth have been modified to the proper amount.

Fig.10 Pressure angle change of nylon gear in the course of operation.

Fig.11 shows the relation between the decreased value from 20 degrees and $T_c \cdot (T/b)$. The decreased value from 20 degrees denotes that the value which is the pressure angle of nylon gear in Fig.10 subtracted from 20 degrees, is added to $[\Delta\alpha]$ in the expression (1) - s in Fig.5). (The value of vertical axis in the figure is the decreased value from 20 degrees.) This value comes close to the solid line which was denoted by $\Delta\alpha$ in the expression (1). Therefore judging from Fig.11 and Fig.9, $\Delta\alpha$ of expression (1) is a reasonable amount of profile modification of steel gear. But in this case there is a problem about the method of profile modification of steel gear. In this experiment like Fig.5 there was a roundness and not a corner at the starting point of modification of tooth profile in the steel gear. But a pressed hollow occurred at the starting point of modification on the tooth surface of nylon gear, as shown in the experiment III-A-1 of Fig. 8(b) because the roundness amount was insufficient. This hollow had a tendency to become large when the value of $T_c \cdot (T/b)$ was large.

4.3 Noise

Fig.12 shows an example of the change of all sound pressure (all pass) level in the course of operation of this experiment. In this figure the broken line shows the all sound pressure level of nylon gear, which meshed with the steel gear of no modification in tooth profile for comparison.

When the mating steel gear had the tooth profile modified, there was nothing showing the frequency characteristic of noise. But in the comparison of all sound pressure levels, there was recognized a difference as shown in Fig.12. If the tooth profile of the mating steel gear was modified to the extent in Fig.5, the sound pressure level dropped, as compared with the meshing with the steel gear of no modification in tooth profile. This depends on the number of rotations (rpm) or the profile of gear. For example, at $N_T = 1.5 \times 10^6$, the sound pressure level was down from 3 to 5 dB. This was because a phenomenon of scooping out of dedendum was relieved. The phenomenon occurred when the addendum of steel gear meshed with the tooth of nylon gear.

4.4 The temperature of tooth of nylon gear

The rise in temperature of tooth of a nylon gear, which meshed with a profile modified steel gear, was the same as that of one, which meshed with a non-profile modified steel gear. And there was a range which was expressed by the relation between the PV value (P : steel gear equivalent Hertzian stress N/m^2 , V : average sliding velocity on the tooth profile m/s) and the rise in temperature of tooth.(7)

5. Conclusions

For the purpose of prevention of

Fig.11 Examination of the amount of profile modification $\Delta\alpha$ of steel gear from experimental results.

Fig.12 Comparison of the all sound pressure level of nylon gear in terms of profile modification or not of steel gear.

tooth profile change of nylon gear, which meshes with steel gear, the tooth profile of steel gear should be modified. The experimental results, in which the nylon gear meshed with the steel gear, are as follows.

(1) When the tooth profile of steel gear is modified, the abrasion is small between the starting point of action and the near pitch point of nylon gear. And the tooth profile change (pressure angle change) of nylon gear decreases.

(2) Examining the experimental results, the reasonable value of profile modification of steel gear, which meshes with the nylon gear, is found to be $\Delta\alpha$ of expression (1).

(3) When the tooth profile of steel gear is modified, the all sound pressure (all pass) level of nylon gear is down. (For example, when the total number of rotations $N_T = 1.5 \times 10^6$ in the experiment I-A group, the all sound pressure level is less than that of the steel gear of no modification in tooth profile, 3~5 dB.)

When the tooth profile of steel gear is modified, the abrasion of nylon gear becomes small, and its life of operation is lengthened.

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(N.B.)

The steel gear equivalent Hertzian stress is a contact stress obtained by hypothesizing and calculating the contact between two steel gears instead of the contact between a nylon gear and a steel gear.