534.83:621.833:678.675

Paper No. 207-18

Noise and Transmission Efficiency

under Deformation of Tooth Form of Nylon Gear*

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Plastic gears are used when steel gears have problems in noise and lubrication. But as there are not actual result data on plastic gears, the plastic gears are little used. When nylon gears were run for power transmission, an abrasion, a deformation of tooth form and a life were investigated.

In this investigation, changes in noise and transmission efficiency have been investigated when the tooth form of nylon gear is deformed in the course of running.

Key Words: Machine Element, Nylon Gear, Tribology, Wear, Sound, Transmission Efficiency, Tooth

1. Introduction

When a steel gear is designed and the design is restricted by noise and lubrication, a plastic gear is usually used instead of a steel gear. But because plastic gears are rarely used for power transmission, there are apprehensions not only about the load capacity but also about noise and power transmission. There is a problem whether the noise becomes low practically when the plastic gear is used, and whether the power transmission of plastic gear is the same as that of steel gear. After all, plastic gears are not used generally. This is because actual results data are scarce. If reliable data in each field are available, plastic gears will come to be used.

One of authors has investigated⁽³⁾⁽⁴⁾ the modes of tooth profile deformation when a nylon gear for power transmission was run, and found that the tooth profile was deformed largely because of abrasion and plastic deformation. This did not occur when the gears transmitted a small power. But at the gear whose tooth profile was deformed, the apparent operation was smooth and to the sense of hearing nylon gears were more silent than steel gears.

In this report the preceding results are confirmed by some apparatus. And it is examined how the noise of gear is low when the tooth profile is deformed largely

for the power transmission in nylon gear, and how the transmission efficiency of nylon gear is reliable like that of steel gear.

2. Experimental apparatus and method

2.1 Gear testing rig

A gear testing rig used in this experiment is a power circulating type. The center distance is 135 mm. This testing machine is same as the one used in the previous report.⁽²⁾ For measurement of the noise of gears, the test gears and the gear box are isolated from the other parts of the rig, that is, those are

Fig. 1 Schematic drawing of gear testing rig and measuring apparatus

* Received 13th October, 1980.

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Table 1 Specification of test gears

	I type		II type		III type	
	Driving gear	Follower	Driving gear	Follower	Driving gear	Follower
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 cutting	Hobbing		Hobbing		Hobbing	
Accuracy	JIS B1702, Grade 4~5		JIS B1702, Grade 4~5		JIS B1702, Grade 4~5	

N.B.) 1, Driving gear is made of MC nylon⁽¹⁾ and follower is made of S45C

2, A unit of module, diameter of standard pitch circle, face width and center distance is mm.

Fig. 2 Tooth profile diagram of steel gears, which mesh with nylon gear

housed in a no-noise room separately, as shown in Fig.1.

2.2 Test gear and meshing gear

Three specifications of test gears adopted in this experiment are shown in Table 1, and these specifications are selected so that the producibility of this experiment can be confirmed. Both nylon gear and steel gear were cut by hob. The backlash was 0.075 module in the nylon gear and 0.04 module in the steel gear. Fig.2 shows a sample of the tooth profile accuracy in each steel gear.

2.3 Measurement of tooth profile

The tooth profile was measured by the same method as in the previous report.⁽⁴⁾

The test gear and the reference gear were fitted together at the gear fitting arbor of basic circle plate type tooth profile measuring apparatus. And the tooth profile and the tooth trace of both tooth surface were measured for every total number of rotations set (gross rotational frequency). The standard gear was a gear which did not run. The gear was a base gear. The deformed quantity of tooth profile of test gear was measured by comparing with this standard gear.

2.4 Measurement of abrasion weight

The abrasion weight of each nylon gear was measured by a dial scale whose measuring accuracy was 10^{-5} g (10^{-4} gf).

2.5 Measurement of gear noise

The noise of gear was measured by a microphone which was fitted at position of 0.3 m from gears in the gear box and in the axial direction to the tooth meshing part. Frequency characteristic was examined by a precision sound level meter, a 1/3 octave band analyzer and a driving unit. In addition, the results were recorded by a high speed level recorder, and the all sound pressure (all pass) was measured simultaneously.

2.6 Measurement of transmission efficiency

The transmission efficiency was calculated by a torque ratio of input and output axes. these torque values were measured by a torque meter.

2.7 Measurement of tooth temperature of nylon gear

Table 2 Experimental conditions and symbols

I type gear			
Number of rotations s ⁻¹ (rpm)	8.3	16.6	25
	(500)	(1000)	(1500)
Torque N·m(kgf·m)			
18.62 (1.9)	I-A-1	I-A-2	I-A-3
10.58(1.08)	I-B-1	I-B-2	I-B-3
II type gear			
23.52(2.4)	II-A-1	II-A-2	II-A-3
19.6 (2.0)	II-B-1	II-B-2	II-B-3
III type gear			
17.64(1.8)	III-A-1	III-A-2	III-A-3
10.29(1.05)	III-B-1	III-B-2	III-B-3
7.35(0.75)	III-C-1	III-C-2	III-C-3

Table 3 Life of nylon gear

Experimental symbols	Total number of rotations up to crack occurrence	Total number of rotations when the operation stopped
I-A-1	20.20x10 ⁵	30.0 x10 ⁵
I-A-2	25.74x10 ⁵	30.0 x10 ⁵
I-A-3	58.30x10 ⁵	60.0 x10 ⁵
I-B-1	—	10 ⁷
I-B-2	—	10 ⁷
I-B-3	—	10 ⁷
II-A-1	4.71x10 ⁵	6.0 x10 ⁵
II-A-2	26.0 x10 ⁵	30.0 x10 ⁵
II-A-3	51.4 x10 ⁵	60.0 x10 ⁵
II-B-1	5.42x10 ⁵	9.4 x10 ⁵
II-B-2	29.1 x10 ⁵	30.0 x10 ⁵
II-B-3	56.2 x10 ⁵	60.0 x10 ⁵
III-A-1	7.8 x10 ⁵	8.6 x10 ⁵
III-A-2	8.18x10 ⁵	9.06x10 ⁵
III-A-3	10.57x10 ⁵	14.27x10 ⁵
III-B-1	—	10 ⁷
III-B-2	—	10 ⁷
III-B-3	—	10 ⁷
III-C-1	—	10 ⁷
III-C-2	—	10 ⁷
III-C-3	—	10 ⁷

Fig. 3 Tooth temperature of nylon gear and room temperature in this experiment

The tooth temperature was measured by the same method as in the previous report.⁽¹⁾ A hole (diameter 1.2 mm) on a pitch circle of gear was bored from the side of tooth to the center of face width. A thermocouple was plugged in the hole and the temperature was measured through a slip ring.

2.8 Experimental conditions

Table 2 shows the torque and the number of rotations in the experiment. In this table, the first of experimental symbols denotes the type of gear, the second the classification of torque and the third the classification of number of rotations. These nylon gears were driving gears and no lubricant running condition was adopted.

3. Experimental results and discussions

3.1 Life and tooth temperature of nylon gear

In the experiment a breakage of nylon gears was originated by a crack near the pitch point of tooth as in the experiment of previous reports.^{(1)~(3)} Table 3 shows the total number of rotations up to the occurrence of a crack and the total number of rotations when the running stopped. The running of nylon gear was continued after the occurrence of the crack, because there were other objects which should be confirmed besides the objects of this experiment. Total number of rotations when the crack occurred on the tooth surface as shown by Table 3 was regarded as the life of nylon gears. The relation between those values and the product $Tc \cdot (T/b)$ is nearly similar to the case of Fig.5 in the previous report (3). The product $Tc \cdot (T/b)$ is multiplication of the contact period of tooth of nylon gear Tc (sec.) by the torque per unit face width T/b (T :torque N·m, b :face width m). Therefore the life of nylon gear became short when the value of $Tc \cdot (T/b)$ value was large.

Fig.3 shows the temperature of tooth of each nylon gear used in this experiment. The temperature of tooth of nylon gear was shown in the previous reports. The specifications of the nylon gear used in this experiment and the operational torque are nearly the same as those of the nylon gear in the previous reports, therefore the temperature in Fig.3 is almost equal to that of the previous report.

3.2 Abrasion

In this experiment the abrasion weight of nylon gear was measured when the

Fig. 4 Abrasion of nylon gear according to product of torque per unit face width of nylon gear and contact period of tooth

total number of rotations N_T were equal to 10^4 , 10^5 , 6×10^5 , 1.5×10^6 , 3×10^6 , 6×10^6 , 10^7 . Fig. 4 shows the relation between the specific abrasion weight and $T_c \cdot (T/b)$ in the course of running time. The abrasion weight of nylon gear is expressed by the specific abrasion weight [abrasion weight kg/ (steel gear equivalent Hertz's stress N/m^2) / number of teeth/face width m/ total number of rotations]. The steel gear equivalent Hertz's stress is same as that in the previous report. (2) This steel gear equivalent Hertz's stress is the contact stress calculated by regarding the intermeshing of the nylon gear with the steel gear as that of a pair of the steel gears. Moreover, the reason that the abrasion of nylon gear can be put in order by $T_c \cdot (T/b)$, is as follows. In the nylon gear used for power transmission, the larger the value of $T_c \cdot (T/b)$ is, the larger becomes the tooth profile deformation. For this reason, the tooth contact pressure becomes larger partially, and the abrasion of the nylon gear is influenced considerably by this pressure.

In Fig. 4, the specific abrasion weight was large in the first stage of running when the total number of rotations N_T was small. And the inclination of the specific abrasion weight to $T_c \cdot (T/b)$ is smaller than when N_T is equal to 1.5×10^6 rotations or over. This seems to be due to the following. The specific abrasion weight was large because initial abrasion. During this running when the deformation of tooth profile was small comparatively, the specific abrasion weight was not influenced by the value of $T_c \cdot (T/b)$. In the cases when N_T is equal to $(1.5 \sim 3) \times 10^6$ and over, because the back-

Fig. 5 (a)

Fig. 5 (b)

Fig. 5 (c)

Fig. 5 Tooth profile

ward inclination of teeth of nylon gear (when a load acts on the teeth of nylon gear, the teeth are inclined⁽⁴⁾ backward due to the plastic deformation) settles to

Fig. 6 (b)

a constant value, the tooth contact force state becoming settled. And the specific abrasion weights for total number of rotations approach each other.

3.3 Tooth profile deformation

The actual state of the life of nylon gear, the temperature of tooth and the abrasion of tooth could be seen from Table 3, Fig.3, Fig.4 etc. mentioned above. In this chapter the deformation of tooth profile will be examined.

Fig.5(a)~(c) show the tooth profile recording diagrams in the course of the running of each nylon gear. N_T is equal to 0 in each diagram showing the tooth profile before running. In these diagrams each curve is drawn by moving as abrasion quantity of tooth from that when N_T is equal to 0. The tooth profile begins to deform largely from the time when N_T is equal to 10^5 or 6×10^5 in each type gear, except in the case of III-C which is low torque running. The tooth profile deformation is large from the starting point of action K to the pitch point P and is small from P point to the tip of tooth Ti. This shows the typical deformation state of tooth profile of nylon gear for power transmission. Because the tooth profile deformation is large in the section between K and P, the abrasion becomes large in this section. As in the nylon gear for

power transmission the teeth incline backward at the starting point of dedendum side as shown in the chapter mentioned above, the addendum side contacts weakly and the dedendum side contacts strongly, and the dedendum side abrades heavily.

In the case of the nylon gear the tooth profile deformation in low speed running is more than in high speed running. This is because in low speed running the contact period of tooth $[(\text{number of teeth} \times \text{number of rotations rpm})/60]$ is long, that is, the torque acting time is long. When this theory is applied, the contact period of tooth in III type gear would be longer than those in I type and II type gears. Therefore the tooth profile deformation in III type gear is larger than those in I type and II type gear. Comparing the results of I-A, II-B with those of III-A whose torques are same level, the tooth profile deformation of III type gear is the largest of all.

3.4 Noise

Fig.6 (a)~(c) show the frequency characteristics of noise in each running of nylon of gear, meshing with steel gear. In each figure the positions of each tooth-meshing frequency f_z and twice the frequency $2f_z$ are written. When the nylon gear meshes with the steel gear, the sound pressure levels of the tooth meshing fre-

Fig. 6 (c)

Fig. 6 Frequency characteristic of noise of nylon gears

Fig. 8 (a)

Fig. 8 (b)

Fig. 8 (c)

Fig. 8 Frequency characteristic of noise of a pair of steel gears

Fig. 7 (a)

Fig. 7 (b)

Fig. 7 (c)

Fig. 7 Crack states of nylon gear

Fig. 9 (b)

Fig. 9 (c)

Fig. 9 (a)

Fig. 10 Change of all sound pressure level of nylon gear in the course of operation

Fig. 9 Change of pressure angle of nylon gear in the course of operation

quency and twice the frequency are high in the same manner as the sound pressure level in the case when a pair of steel gears mesh with each other. But when the frequency is near 1.3kHz and over, the sound pressure level is low remarkably. As the sound pressure level of this high frequency band is low, the noise of nylon gear is low probably. With a change of sound pressure level in the running of nylon gear, the sound pressure level becomes much higher after long time running generally. But at several frequencies the sound pressure level is not always higher.

The frequency characteristic of the gear, which broke before 10^7 rotations (total number of rotations) is not different from that of the non-broken gear. Gear broke in cases of I-A, II-A, III-B and III-A. The photographs of Fig.7 (a), (b) show cracks on tooth surfaces of I-A-3, II-B-3. The frequency characteristics of these nylon gears do not change under this degree of cracking or in the initial stage of cracking. But when a big crack occurs on the tooth surface as shown in III-A-3 of photograph of Fig.7(c), the sound pressure level in high frequency is high remarkably as shown in III-A-3 of Fig.6. It seems that the noise occurs when a crack occurs from teeth.

Fig.8 (a)-(c) show the frequency characteristic of noise of a pair of steel gears meshed in the same running condition as that of nylon gear. The lubrication of gears is done by hand before running because the running is only needed for measurement of noise.

Fig.8 (a)-(c) correspond to the experiments of I type, II type and III

type nylon gears respectively. When Fig.6 is compared with Fig.8, the sound pressure level of the case of intermeshing of a pair of steel gears is found high in a high frequency band of over 1 kHz. Especially at 1500 rpm, the sound pressure level is high about 100 dB. But the sound pressure level of nylon gear is much lower than that of steel gear.

As shown in Fig.6, the change of noise accompanying the deformation of tooth profile was not clear although the frequency characteristic of gear noise was examined in the course of running, and then would be discussed the change of all sound pressure level of noise and the change of pressure angle of tooth profile of nylon gear in the course of running.

Figs.9, 10 show respectively the change of pressure angle of each nylon gear in the running and the change of all sound pressure level of noise. The tendency of the change of pressure angle is as follows. The pressure angle changes largely from the start of running to 1.5×10^6 rotations, and hardly changes after the rotations. But when number of teeth is small (like III-B) and T_c is long, besides the torque is large (but teeth did not break at this torque), the change of pressure angle stops temporarily, but the pressure angle changes after that. As the experiments were stopped when the pressure angle changed largely in II-A, II-B, III-A, the change of pressure angle after that could not be known. On the other hand, the all sound pressure level of noise generally changed largely up to 6×10^5 or 1.5×10^6 rotations and hardly changed after that. Comparing Fig.9 with

Fig. 11 Change of transmission efficiency of nylon gear in the course of operation

Fig.10, the all sound pressure level changed with the change of pressure angle in the first stage of running mainly. Therefore when the teeth of nylon gear is inclined⁽⁴⁾ backward at the dedendum side, the all sound pressure level is high, and after that the all sound pressure hardly changes when the teeth abrade and the pressure angle change. Comparing of the all sound pressure level (all pass) of steel gear of Fig.8 with that of Fig.10, the all sound pressure level of power transmission nylon gear is hardly different from that of steel gear.

3.5 Transmission efficiency

Fig.11 shows the change of transmission efficiency in the course of running. The vertical axis shows the transmission efficiency ratio (the transmission efficiency in each running/ the transmission efficiency just after running started) $\times 100(\%)$. The vertical axis is used because the nylon gear is removed in order to measure the abrasion weight of nylon gear and the tooth profile for all of the total numbers of rotations set. The transmission efficiency just after running of nylon gear is from about 93 to 97% in this experiment. And the axial torque on the torque meter varies at a certain width. In this experiment the average of those torques is adopted.

As shown in Fig.11 the transmission efficiency decreases largely up to near $10^6 \sim 1.5 \times 10^6$ rotations. And after that the efficiency hardly decreases. Therefore the transmission efficiency would be changed mainly in the first stage of running in the same manner as in the case of noise.

4. Conclusions

In this paper, an investigation about the tooth profile deformation the noise and the transmission efficiency of power transmission nylon gear was made. The following results have been obtained.

- (1) Teeth of nylon gear incline backward from the dedendum when the load acts on them. Therefore, the load becomes small at the addendum side and large at the dedendum side. Because the abrasion of tooth is influenced largely by the state of the load, the

abrasion of tooth can be regulated by the product $T_c \cdot (T/b)$ of contact period of tooth T_c and torque per unit face width (T/b) .

- (2) The tooth profile deformation of nylon gear in the course of running is caused by abrasion of tooth. The abrasion is large from the starting point of action to the pitch point and small from the pitch point to the addendum. The larger the value of $T_c \cdot (T/b)$, the larger becomes the tooth profile deformation.
- (3) The noise of nylon gears is lower than the noise of steel gears because the sound pressure level is low when the frequency band is about 1.3 kHz and over. When the tooth profile of nylon gears changed in the running, the frequency characteristic of noise did not change clearly. But the all sound pressure level changes in the first stage of running time up to 6×10^5 or 1.5×10^6 rotations (the all sound pressure level becomes large).
- (4) The transmission efficiency in the course of running changed in the first stage of running mainly in the same manner as in the case of noise. (The transmission efficiency becomes low.) And after that, the transmission efficiency hardly changes.

The authors wish to thank Dr. K. Umezawa, Assistant Professor of Tokyo Institute of Technology for his guidance and researchers and students of Umezawa laboratory for their helpful suggestions.

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