Investigation about Load Capacity of Nylon Gears, when Tooth

Surface Finishing of Mating Steel Gears is different

(2nd Report; Abrasion of Nylon Gear Meshing with Ground Steel Gear)*

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In the eariler report, it was investigated basically how the surface roughness of a steel cylinder influenced the abrasion of a nylon cylinder. In this report, steel gears were ground to several degrees of roughness by 0° teeth ground method of MAAG. And it has been investigated through the experiment how these roughnesses of teeth of steel gears influence the abrasion of nylon gears. These results were compared with the abrasion of a nylon gear, which meshed with a hobbled steel gear. In the intermeshing with a power transmission nylon gear, it has been found that a steel gear whose teeth have been ground, is useful.

Key Words: Machine Element, Plastic Gear, Nylon Gear, Tribology, Wear, Tooth Surface Roughness

1. Introduction

In the earlier report⁽¹⁾, it was reported that the surface roughness of a steel cylinder influenced the abrasion of a nylon cylinder when the steel cylinder and the nylon cylinder contacted in a rolling sliding. It is difficult to estimate the abrasion of a nylon gear, meshing with a tooth ground steel gear, from this test results. Because the contact mechanism of the cylinder is different from that of the gear essentially. When the surface roughness of a steel gear is different a little, the abrasion of the nylon gear is not different. Because the tooth of a visco-elastic gear deforms when the nylon gear receives a big power, since the gear tooth is like a cantilever, not like a cylinder. Intermeshing of a deformed gear is different from the theoretical intermeshing. Therefore this difference influences the abrasion largely. Then in the intermeshing of nylon gear and steel gear which transmit a power, it is a doubtful that the grinding of steel gear teeth is a very useful means for the abrasion prevention of nylon gear.

In this report an experiment was performed with a steel gear and a nylon gear. The steel gear teeth were ground to several surface roughnesses by MAAG 0 degree ground method. Influence on the nylon gear was compared with the abrasion of a nylon gear, which meshed with a hobbled steel gear. It was found that the ground steel gear which meshed with the power transmitted nylon gear was useful.

2. Experimental Apparatus and Method

2.1 Gear testing rig

Fig.1 shows a gear testing rig employed in this experiment. The rig is a power circulating gear testing rig whose center distance is 135 mm. The power is supplied to the rig through ⑩ V-belt. The load is applied by ⑦ torsional load coupling. The torque value is confirmed by ⑧ torque pick-up. ⑨ and ⑨' slip rings are used to measure the temperature of gear teeth in the nylon gear and the steel gear.

Fig.1 Gear testing rig

* Received 25th January, 1982.

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Table 1 Specifications of test gear

	Type I		Type II	
	Driving gear	Driven gear	Driving gear	Driven gear
Module	3		5	
Standard pressure angle	20°		20°	
Number of teeth	30	60	17	37
Addendum modification coefficient	0	0	0	0
Diameter of standard pitch circle	90	180	85	185
Clearance coefficient	0.25		0.25	
Center distance	135		135	
Face width	10	10	10	10
Teeth finishing	Hobbing	Grinding	Hobbing	Grinding

N.B.) Driving gear is made of MC nylon⁽⁴⁾ and driven gear is made of SNC415

Fig. 2 Steel gear, which meshes with nylon gear

2.2 Test gear and meshing gear

Two specifications of test gears adopted in this experiment are shown in Table 1. Nylon gears in each type looked like circular plates, whose thickness was equal to tooth width. Steel gears in each type had a light weight, as shown in Fig. 2. The abrasion mass is measured by a dial scale, whose capacity is limited. Nylon gears of each type had been cut by hobbing. Steel gears of each type had been ground by 0 degree tooth grinding machine of MAAG, except in an additional experiment. The index values of the surface roughness of ground steel gear were 3S and 6S of JIS B0601. But the surface roughness of the tooth profile direction of finished gear was $0.6 \sim 0.8 \mu\text{m}$ and $2.2 \sim 2.6 \mu\text{m}$ in ten point average (R_z) of JIS B0601, as shown in Fig. 3. And the ground steel gear was carburized. The hardness

Fig. 3 Tooth surface roughness of steel gear

Fig. 4 Tooth profile record diagram of steel gear, which meshes with nylon gear

of tooth surface was $HRC = 58 \sim 62$. The backlash was 0.075 module in nylon gear and 0.04 module in steel gear. Fig. 4 illustrates the accuracy of tooth profile of each type steel gear.

Fig.5 Measuring position of tooth temperature

2.3 Measurement of abrasion mass

The abrasion mass of nylon gear and steel gear was measured in the course of operation by a dial scale whose measuring accuracy was 0.1 mg (10^{-4} g).

2.4 Measurement of tooth profile

A change in the tooth profile was measured by the same method as in the previous report(3). The test gear and the standard gear were fitted together at the gear fitting arbor of the basic circle plate type tooth profile measuring apparatus. And the tooth profile and the tooth trace of both tooth surfaces 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 in measuring. The deformed quantity of tooth profile of test gear was measured by comparing with this standard gear.

2.5 Measurement of tooth temperature

In the measurement of tooth temperature in nylon and steel gears, a thermocouple was used. The thermocouple was plugged in a hole, 1.2 mm in diameter which was bored from the side of tooth to the center of face width at pitch circle of the gear as shown in Fig.5. The temperature was measured through a slip ring.

2.6 Measurement of tooth surface roughness

In the measurement of tooth surface roughness of nylon gear and steel gear, a replica of triacetylcellulose film was taken and the replica was measured by a stylus type roughness testing rig. The roughness adopted was ten point average (JIS B0601). The base length was 2 mm and the cut off value was 0.075 mm. In this report, the surface roughness is a roughness in the tooth profile direction.

2.7 Experimental conditions

Table 2 gives two kinds of torques, three numbers of rotations and two kinds of tooth surface roughnesses of steel gear in both type I and type II gears in this

Table 2 Experimental conditions and symbols

type I gear				
Torque N·m (Kgf·m)	Number of rotations s ⁻¹ (rpm)	8.3	16.6	25.0
	Tooth roughness of mating steel gear (μm)	(500)	(1000)	(1500)
11 (1.1)	Rz = 0.6 ~ 0.8	I-A-1	I-A-2	I-A-3
	Rz = 2.2 ~ 2.6	I-B-1	I-B-2	I-B-3
8.5 (0.85)	Rz = 0.6 ~ 0.8	I-C-1	I-C-2	I-C-3
	Rz = 2.2 ~ 2.6	I-D-1	I-D-2	I-D-3
type II gear				
11 (1.1)	Rz = 0.6 ~ 0.8	II-A-1	II-A-2	II-A-3
	Rz = 2.2 ~ 2.6	II-B-1	II-B-2	II-B-3
8.5 (0.85)	Rz = 0.6 ~ 0.8	II-C-1	II-C-2	II-C-3
	Rz = 2.2 ~ 2.6	II-D-1	II-D-2	II-D-3

Fig.6 Abrasion of nylon gear in the course of operation

Fig.7 Abrasion of nylon gear, which is based on the product of torque per unit face width of nylon gear and contact period of tooth

experiment. In this table the first experimental symbol denotes a type of gear, the second a combination of torque and tooth surface roughness and the third a number of rotations. In each experiment, the nylon gear was a driving gear and no lubricant operation was performed.

3. Experimental Results and Discussion

3.1 Abrasion

Fig.6 illustrates a progress state of abrasion in the course of operation of a

nylon gear which meshed with a tooth ground steel gear. In this figure the number of rotations is invariably 16.6 s^{-1} (1000 rpm). In each figure the results of abrasion experiment of a nylon gear, which meshed with the hob cut steel gear (the tooth surface roughness and tooth profile accuracy are shown in Fig.3 and Fig.4) are shown by a one point chain line. This experimental condition is the same as the condition of the nylon gear which meshed with the ground steel gear [number of rotations 16.6 s^{-1} torque $11 \text{ N}\cdot\text{m}$ and $8.5 \text{ N}\cdot\text{m}$ ($1.1 \text{ kgf}\cdot\text{m}$ and $0.85 \text{ kgf}\cdot\text{m}$)].

In Fig.6 a gross abrasion mass of the nylon gear which meshed with the ground steel gear in the course of operation is less than that of the nylon gear which meshed with the hob cut steel gear. And the abrasion of nylon gear which meshed with the ground steel gear, whose tooth surface roughness was small, was a little. But the gross abrasional mass differed from each largely in the total number of rotations 3×10^6 or 6×10^6 . And after that the difference of the gross abrasional mass did not spread.

Next after the abrasion until a total number of rotations is arranged by the other method than in Fig.6, the abrasion of a nylon gear which meshed with the hob cut steel gear will be compared with that of the one which meshed with the ground steel gear. Fig.7 shows all of the abrasion results of this experiment. The vertical axis indicates the specific abrasion weight [abrasion mass $\text{mg}/(\text{steel gear equivalent Hertzian stress } \text{N}/\text{m}^2)/\text{number of teeth}/\text{face width } \text{m}/\text{gross rotational frequency}$]. The horizontal axis indicates $T_c \cdot (T/b)$. T_c is the contact period of teeth [a reciprocal number of (number of teeth $\times$ number of rotations $\text{rpm}/60$)]. (T/b) is the torque per unit face width (T :torque $\text{N}\cdot\text{m}$, b :face width m). The steel gear equivalent Hertzian stress in the specific abrasion weight in the vertical axis 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, as shown in the earlier report (2),(3),(4). As T_c in the horizontal axis corresponds to a time when a tooth moves along the line of action, the length of normal pitch, $T_c \cdot (T/b)$ means a quantity of action of torque per unit face width in fixed time.

Δ signs in Fig.7 denote the abrasion of a nylon gear, which meshed with the hob cut steel gear in the earlier experiment report (2),(3) and in this experiment. The abrasion of the nylon gear, which meshed with the ground steel gear is put in order in terms of $T_c \cdot (T/b)$ the same as the abrasion of the nylon gear, which meshed with the hob cut steel gear, as shown in this figure. Comparing the two nylon gears, in the early stage of operation, the abrasion of the nylon gear, which meshed with the ground steel gear, is less than the abrasion of the nylon gear, which meshed with the hob cut steel gear, for example the total number of rotations $N_T = 10^5$. When N_T

Fig.8 Change of tooth profile of nylon gear, which meshes with teeth ground gear

increases, the abrasion difference is very little. The two abrasions come close to each other at $N_T = 3 \times 10^6$ or 6×10^6 and there after. Comparing the tooth surface roughness $R_z = 2.2 \sim 2.6 \mu\text{m}$ and $R_z = 0.6 \sim 0.8 \mu\text{m}$ of mating teeth ground steel gear, the tendency in the abrasion of the nylon gears is same as that in the abrasion of nylon gears, which meshed with the hob cut steel gear and ground steel gear. That is, when N_T increases, the difference in abrasion of nylon gear due to the difference in the roughness of tooth surface is not remarkable.

Therefore in the early stage of operation it is useful as an abrasion countermeasure to grind the teeth of a meshed mating steel gear and make the tooth surface roughness small. But when the operation is long, ground teeth have little effect. In that case the abrasion countermeasure for nylon gear must be considered taking account of the price of teeth ground gear.

3.2 Abrasion distribution on a tooth profile and change of a tooth profile

Fig.8 shows a sample of tooth profile record diagram of a nylon gear, which

Fig.9 Concept illustration of abrasion distribution on the tooth profile and change of tooth profile of nylon gear

meshed with a teeth ground steel gear. In this figure a line of $N_T=0$ shows a tooth profile record diagram before operation. A tooth profile diagram for each total number of rotations is drawn at intervals of the quantity of abrasion from the diagram of $N_T=0$. Therefore an interval in each tooth profile diagram indicates the abrasion distribution on the tooth profile.

The abrasion distribution on the tooth profile and the change in tooth profile of a nylon gear, which meshed with a teeth ground steel gear, are the same as those of a nylon gear, which meshed with the hob cut steel gear in the earlier report (3). That is to say, after the early stage of operation the abrasion grew large from the starting point of action K to the pitch point P and the tooth profile changed remarkably. As the abrasion was small between P point and the tip of tooth T_i, the change in tooth profile was a little. Especially in II-B-1 of Fig.8 of type II nylon gear, these things appeared clearly. Fig. 9 shows a concept diagram of tooth profile change of nylon gear in II-B-1 when the change due to plastic deformation is ignored. This is a typical change form of tooth profile of a driving nylon gear, which transmitted the power. This form does not change at all whether the mating gear is a hob cut steel gear or a teeth ground steel gear. As the tooth profile of the power transmitting nylon gear changes like this, the abrasion of nylon gear does not decrease even when the teeth of mating steel gear are ground.

Considering the above-mentioned abrasion distribution on the tooth profile and the change of tooth profile and comparing Fig.7 with Fig.9, the following may be stated.

At the stage of $N_T=10^5$ where the distribution of abrasion on the tooth profile of Fig.9 is almost uniform and a change in tooth profile does not occur yet, the abrasion of the nylon gear, which meshes with the teeth ground steel gear is clearly less than the abrasion of the nylon gear, which meshes with the hob cut steel

Fig.10 Contact state of driving nylon gear

gear as shown in Fig.7. When the abrasion from the starting point of action to the pitch point is larger than the abrasion from the pitch point to the tip of tooth in the course of operation, the difference between the abrasion of the nylon gear, which meshes with the teeth ground steel gear, and the abrasion of the nylon gear, which meshes with the hob cut steel gear is a little. Therefore if the abrasion of the nylon gear is equalized on the tooth profile in the operation, the teeth ground of steel gear will be effective as the abrasion counter measure for the nylon gear. But as the deflection of tooth (2) of nylon gear becomes maximum at the end M of a pair meshing when the driving nylon gear meshes with the steel gear in Fig.10, these gears begin to mesh with each other when the edge of addendum of tooth (3) of steel gear scoops out the dedendum of tooth (1) of nylon gear. Besides as a tooth (3) is made of steel, the tooth is difficult to deflect and the load at K point is larger than at M point because the tooth (1) is made of nylon but K point is dedendum. Therefore the abrasion is large at the side of starting point of action and as this abrasion dominates all the amount of abrasion of this tooth, the difference of abrasion does not appear depending on the difference of roughness when the tooth surface roughness changes a little. Fig.11 shows the case when the abrasion distribution on the tooth profile is uniform comparatively. Even when the tooth profile changes this degree, the effect of teeth ground of steel gear on the abrasion-proofness of nylon gear does not appear.

3.3 Tooth temperature of nylon gear and abrasion of steel gear

Fig.12 shows the tooth temperature of a nylon gear which meshes with a steel gear. Δ marks in this figure denote the temperature of nylon gear which meshes with a hobbled steel gear in this and previous experiments. And $\square$ in this figure denotes a group in which the number of

Fig. 11 Tooth profile of nylon gear, which has changed a little

Table 3 Abrasion mass of steel gear

Experimental symbols	Abrasion mass of steel gear at $N_T 10^7$ mg(g)
I - A - 1	-1.74(0.0174)
I - B - 1	-0.60(0.0060)
I - C - 1	-0.42(0.0042)
I - D - 1	-0.38(0.0038)
H . G	-0.16(0.0016)
I - A - 2	-1.96(0.0196)
I - B - 2	-0.90(0.0090)
H . G	+0.09(0.0009)
I - C - 2	-0.60(0.0060)
I - D - 2	-0.53(0.0053)
I - A - 3	-0.50(0.0050)
I - B - 3	-0.21(0.0021)
I - C - 3	-0.12(0.0012)
I - D - 3	-0.03(0.0003)
II - A - 1	-0.98(0.0098)
II - B - 1	-0.55(0.0055)
II - C - 1	-0.78(0.0078)
II - D - 1	-0.20(0.0020)
H . G	-0.23(0.0023)
II - A - 2	-1.03(0.0103)
II - B - 2	-0.61(0.0061)
H . G	-0.17(0.0017)
II - C - 2	-0.74(0.0074)
II - D - 2	-0.38(0.0038)
II - A - 3	-0.62(0.0062)
II - B - 3	-0.46(0.0046)
II - C - 3	-0.29(0.0029)
II - D - 3	-0.14(0.0014)

N.B.) H.G; Intermeshing with hobbed steel gear

H.G; Intermeshing with hob cut steel gear
Upper; Balance temperature of tooth
Lower; Room temperature

Fig. 12 Tooth temperature of nylon gear, which meshes with steel gear

rotations and torque are same and the tooth surface roughness of a meshed mating steel gear is different. The lower limit temperature in each experiment is an average temperature of room in the experiment. The upper limit temperature is a balance temperature of tooth. As the temperature of tooth of nylon gear before experiment is almost equal to the room temperature, the temperature rise in tooth comes between the upper limit temperature and the lower limit temperature.

In Fig. 12 the temperature of tooth of a nylon gear which meshes with a mating steel gear whose tooth surface roughness is small, is generally higher a little.

Table 3 shows the abrasion mass of a steel gear which meshes with a nylon gear at $N_T=10^7$ when the experiment ends. The numerical value with + (plus) in this table is one which has decreased compared with the value before operation. The numerical value with - (minus) is one which has increased compared with the value before operation. The reason why the mass of steel gear has increased compared with the value before operation can be surmised as follows: the abrasion powder of the meshed mating nylon gear adheres to the steel gear. The amount of abrasion which adhered to the steel gear is very little. But when Fig. 12 is compared with Table 3, the temperature of tooth of the nylon gear which meshes with the teeth ground steel gear which has much adhered abrasion powder, is found high.

4. Conclusions

The following results have been obtained from the abrasion test of a nylon gear which meshes with a teeth ground nylon gear and compared with the abrasion of a nylon gear which meshes with a hobbled steel gear.

(1) The abrasion of the nylon gear which meshes with the teeth ground steel gear is expressed by a specific abrasion weight [abrasion mass mg/ (steel gear equivalent Hertzian stress N/m^2) / number of teeth/ face width m/ total number of rotations]. The abrasion 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) , like the nylon gear which meshes with the hobbled steel gear.

(2) Comparing the abrasion of a nylon gear which meshes with a teeth ground steel gear with the abrasion of a nylon gear which meshes with a hobbled steel gear by the specific abrasion weight, in the first stage of operation the abrasion in the former is remarkably less than that in the latter. But the difference in abrasion is little with an increasing total number of rotations. Especially the difference becomes the least after the total number of rotations $(3 \sim 6) \times 10^6$.

(3) The abrasion distribution on the tooth profile of a nylon gear which meshes with a teeth ground steel gear, has the same tendency as the abrasion distribution of a nylon gear which meshed with a hobbled steel gear. That is, the abrasion is very large from the starting point of action to the pitch point and small from the pitch point to addendum.

(4) As the abrasion of tooth from the starting point of action to the pitch point dominates all the amount of abrasion of tooth, the difference of roughness is not related with the difference of abrasion when the teeth of steel gear is ground and the roughness of teeth changes. Therefore in the power transmission nylon gear, the teeth ground of a mating steel gear do not have any effect on abrasion-proofness.

(5) The adhesion of abrasion powder of a mating nylon gear to the teeth ground steel gear is larger than that to the hobbled steel gear. The temperature of tooth of a nylon gear which meshes with a teeth ground steel gear to which a large volume of the abrasion powder adheres, is higher than that of a nylon gear which meshes with a hobbled steel gear.

The author wishes to thank Dr. K. Umezawa, Associate Professor of Tokyo Institute of Technology for his guidance and researchers and students of Umezawa laboratory for their helpful suggestions.

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