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Investigation about the Prevention of Tooth Profile Change of Plastic Gears*

(2nd Report; Abrasion and tooth profile change of nylon gear, reinforced with a stiffener)

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When the tooth of a nylon gear of visco-elastic body was applied with a force the tooth deflected largely and a rotational lag occurred at the mating steel gear. This caused an abnormal abrasion at nylon gear tooth flanks and the tooth profile changed conspicuously. In order to prevent these things, the nylon gear was developed. The gear included a stiffener of steel in the core of tooth and the tooth was made hard to deflect.

In this report, the manufacture of this gear was outlined and the characteristic of abrasion and the tooth profile change in the course of operation were made clear.

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

1. Introduction

When a steel gear meshes with a nylon gear, this gear pair can be operated under no lubrication and the gear noise becomes lower than that of a combination of two steel gears. But when this gear pair is operated under a large torque, the abnormal abrasion becomes large from the starting point of action to near the pitch point of tooth of nylon gear. Therefore the nylon gear has the tooth profile in which the pressure angle is largely changed.

This is because when the steel gear meshes with the nylon gear, the tooth of the nylon gear is largely deflected and a rotation lag occurs. This phenomenon occurs when the next tooth begins to mesh, the steel gear contacts with the nylon gear such that the edge of addendum of steel gear scoops out the tooth flank. As the method of preventing this phenomenon we proposed that the tooth profile of steel gear be modified and reported on a reasonable amount of modification in the previous report.(1)

The profile modification of steel gear was effective for the prevention. But it was troublesome to change the modification amount of steel gear each time the operating condition of nylon gear changed.

In this investigation, we noted that the tooth profile change (pressure angle change) of nylon gear was caused by a large deflection of tooth of nylon gear as mentioned above. Thus we designed a nylon gear which included a steel stiffener in the core of nylon tooth to minimize the tooth diflection. In this paper the manufacturing method of this gear is outlined, the abrasion of this gear is investigated and the change state of tooth profile is examined.

2. Outline of Manufacturing a Nylon Gear, Reinforced with a Stiffener

When the gear is made of plastic, which is mixed with carbon fiber or glass fiber, the tooth becomes hard to deflect. But in this case the gear will be expensive and not generally available. In order to manufacture a nylon gear, which is not more expensive than an ordinary nylon gear and has a small teeth deflection, a gear is designed including a steel stiffener in the core of nylon teeth, as shown in Fig.1. (In the following this gear will be called SN-gear.)

The most difficult point in manufacturing the SN-gear is the adhesion of the nylon to the steel stiffener. In this investigation a special technique was not used and in the common manufacturing process of MC nylon material,(2) both materials could be bonded. Therefore the price of this gear is the same as that of the ordinary MC nylon gear.

Fig.2 shows a form and dimensions of a stiffener, which is made of carbon steel (S45C). The radial projection on the circumference is the core of tooth. In this

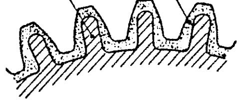

Fig.1 Nylon gear which includs a stiffener of steel in the core of tooth

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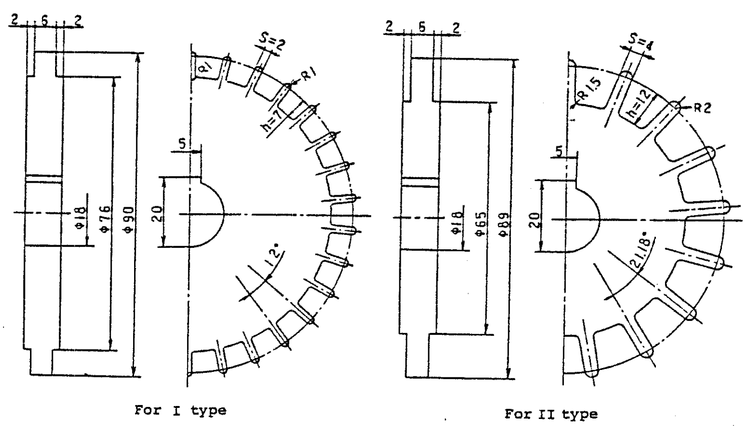


Fig.2 Form and dimension of stiffener of SN-gear

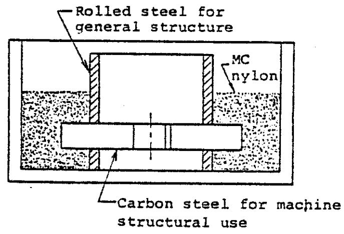


Fig.3 Casting of nylon material

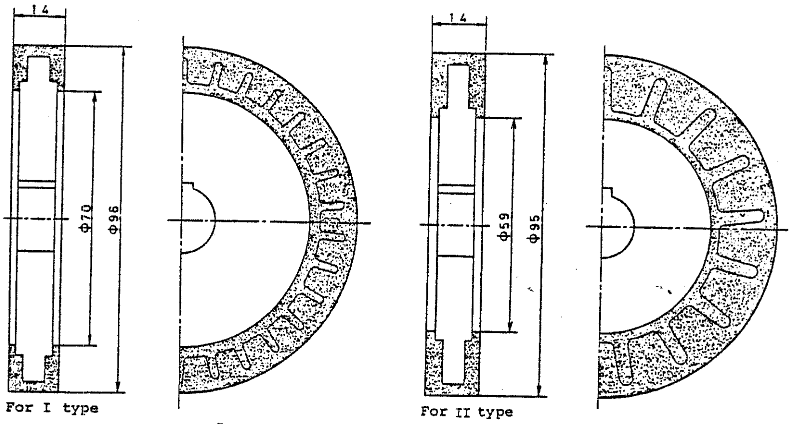


Fig.4 State before the gear cutting of SN- gears

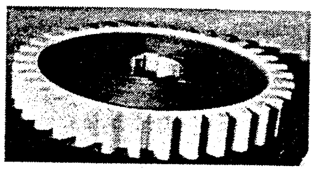


Fig.5 SN-gear, finished by the gear cutting

figure it is desirable that the part s be large. When it is too large, the tooth surface of nylon part becomes thin. Therefore the thickness of s is restricted. When the dimension h is large, the nylon part of tooth crest becomes thin. In this investigation, the dimensions of s and h were decided assuming that the type I and type II gears were operated under the conditions, that the steel equivalent Hertzian stress[3](N.B.) was 343 MPa (35 kgf/mm^2), the total number of rotations was 10^8 and the nylon part remained on the tooth surface. And this dimension was decided by the earlier experiment.[1]~[5] But this stiffener was manufactured by way of trial and this dimension is groundless.

Next the core of Fig.2 was put horizontally in a container as shown in Fig.3. And a molten MC nylon material of 50°c was casted in to this container and the nylon was polymerized. Ingredients of the molten MC nylon material were ε-caprolactam, catelyzer and starting material.

The polymerization finished at about 15 minutes, but the casting was left at it was for about 30 minutes after it was taken out. In the mean time the nylon contracted, and adhered to the steel of stiffener of core by this contracting force. Fig.4 shows how the material was turned by a lathe after casting and was finished to the final dimension before gear cutting. Further the material was annealed with hot water before lathe cutting. The photograph in Fig.5 shows the SN-gear (type I) after gear cutting.

3. Operation Test

When the SN-gear operates for a long time, the nylon may separate from the stiffener and the deflection of tooth may be small or an abnormal abrasion may occur at the tooth flank. As the gear body is made of carbon steel, as shown in Fig.4, there is no guarantee that it generates a low noise which is the advantage of the plastic gear. To make tune about these things the following operation test was performed and the abrasion of gear, the tooth profile change and the noise were investigated.

3.1 Test gear and operating conditions

The operation test was performed about two specification gears of type I and type II, as shown in Table 1 under the torque and the number of rotations, as shown in Table 2.

3.2 Gear testing rig

In this operation test a power circulating gear testing rig,[4] whose center distance was 135 mm, was used. As the gear noise was measured in this experiment too,

Table 1 Specifications of test gears

	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 coeficient	0	0	0	0
Diameter of standard pitch circle	90	180	85	185
Clearance coeficience	0.25		0.25	
Meshing net face width	10	10	10	10
Center distance	135		135	
Teeth cutting	Hobbing		Hobbing	
Accuracy	JIS B1702, Grade 4-5		JIS B1702, Grade 4-5	

N.B.) A unit of module, diameter of standard pitch circle, meshing net face width and center distance is mm.

Table 2 Experimental conditions and symbols

Type I gear			
Number of rotations s^{-1} (rpm) / Torque N·m(kgf·m)	8.3 (500)	16.6 (1000)	25.0 (1500)
17.64 (1.8)	I-A-1	I-A-2	I-A-3
20.58 (2.1)	I-B-1	I-B-2	——
Type II gear			
17.64 (1.8)	II-A-1	II-A-2	II-A-3
20.58 (2.1)	II-B-1	II-B-2	——
Type I′ gear			
20.58 (2.1)	I′-B-1	I′-B-2	——
Type II′ gear			
20.58 (2.1)	II′-B-1	II′-B-2	——

N.B.) All the test was performed under the no lubricant operation. The dash donotes a test condition of improved SN gears.

the test gear and the gear box were enclosed to set them apart from the other part in the same way as in the earlier report.(4)

3.3 Measured item and measuring method

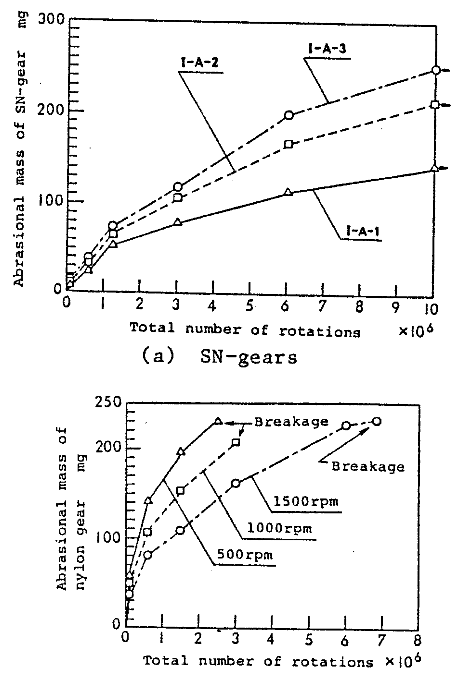
In this experiment, the abrasing, the tooth profile change and the noise of SN-gear were measured the same as in the earlier report.(1),(3),(5) And the tooth surface temperature was measured near the pitch point of the center of face width by a surface thermometer.

4. Test Results and Discussion

4.1 Abrasion

Fig.6(a) shows a result of test I-A group as an example of abrasion in the course of SN-gear operation. The vertical axis shows the total abrasion mass. In this experiment all of type I and type II SN-gear could be operated with no damage up to the total number of rotations (gross rotational repetitions) 10^7 and even in the later operation these gears could be continuously operated because the tooth surface remained good. Common type I and type II nylon gears could not operate up to $N_T=10^7$ with no breakage under the number of rotations 500 ~ 1500 rpm and the torque about 14.7 N.m (1.5 kgf.m) as in this experiment. Therefore it may be called a great merit of the plastic gear that it can operate under the torque 20.58 N.m (kgf.m) like I-B group and II-B group.

Fig.6(b) shows the abrasion of nylon gear as compared with the abrasion of SN-gear under the same test condition of I-A group. Comparing both figures, it is found that the order of the abrasion due to the number of rotations (rpm) is different between the SN-gear and the nylon gear. The abrasion of SN-gear increased when the number of rotations increased, but the abrasion of nylon gear decreased on the contrary. The abrasion of nylon gear became large in low speed rotations. This is because when the number of rotations is small, the force (torque) acts on the tooth



(a) SN-gears

(b) Nylon gears

Fig.6 Comparison of the abrasion between SN-gear and nylon gear

for a long time and the diflection of tooth increases with an abnormal abrasion occuring at the tooth flank as shown in the earlier report(3). Judging from the fact that the abrasion order is different between Fig.(a) and Fig.(b), the deflection of tooth of SN-gear in the operation will be small.

It is interesting that the abrasion of SN-gear is much smaller than that of nylon gear. For example, in the operation at 500 rpm, the abrasion of SN-gear in 10^7 rotations (the total number of rotations) was the same as that of nylon gear in 1.5 x 10^6 rotations. This is because, the deflection of tooth of SN-gear was small as the stiffener was included in the core of nylon tooth and the abnormal abrasion of tooth flank was prevented.

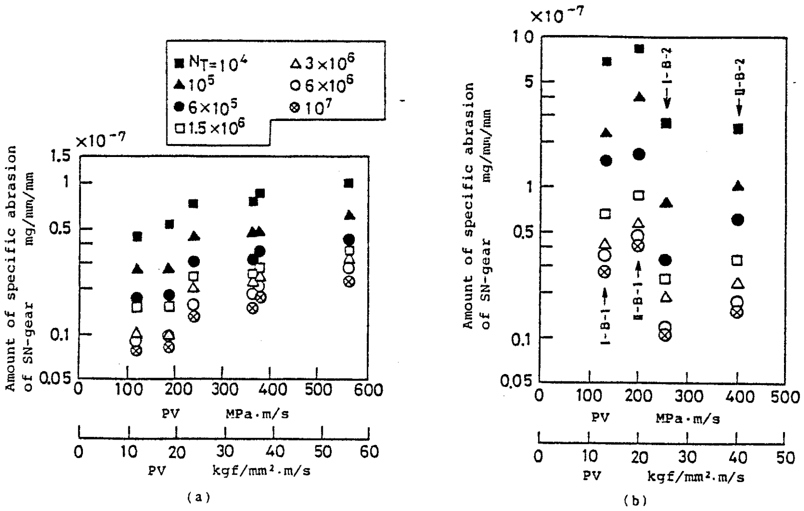


Fig.7 Relation between the amount of specific abrasion of SN-gear and PV value

Next, Fig.7 summarizes all the results about the abrasion of SN-gear in this test in terms of the relation between the amount of specific abrasion [Abrasional mass mg/(Total number of rotations x Number of tooth x Face width mm x 2 module)] and PV value (P: Steel gear equivalent Hertzian stress MPa, V: Average sliding velocity on the tooth profile). The abrasion of SN-gear was replaced by the amount of specific abrasion. Fig.(a) shows the results about I-A group and II-A group, and Fig.(b) the results about I-B group and II-B group. Fig.(a) shows the results when the torque was 17.64 N.m(1.8 kgf.m). The values differed depending on the specifications of gears and the operating conditions. But the value of logarithms in the amount of specific abrasion was proportionate to PV value. With an increasing PV value, the amount of specific abrasion increased. In this figure, the amount of specific abrasion ζ in $N_T=10^7$ can be given by the following expressions.

$$\zeta = 10^{\alpha \cdot PV+\beta} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$
$$\alpha = 1.13 \times 10^{-3}$$
$$\beta = -8.25$$

The unit of ζ is mg/mm/mm and the unit of PV is Mpa.m/s.

On the other hand, Fig.(b) shows operation under a torque larger than that of Fig.(a). In Fig.(b), when PV value was small, the amount of specific abrasion was large, unlike in Fig.(a). As the change of PV value was influenced by the V value, PV value was small when the number of rotations was low. That is to say, in SN-gear in the large torque operation, the abrasion was large in the low rotations just as in a nylon gear as shown in Fig.6(b). This is because, when a large load acted on the tooth of SN-gear, the deflection became large and the abnormal abrasion occurred at the tooth flank.

A phenomenon as shown in Fig.7(b) occurred and the therefore the state of the deflection of tooth of SN-gear was examined. Fig.8 shows the results about the deflection of SN-gear and nylon gear of type II. The deflection was measured by the electronic micro meter in the direction of line of action when the load acted at the tip of tooth. The action time of load was about 3 seconds. In this experiment, in the low load, the deflection of SN-gear turned out smaller than that of nylon gear. But when the load increased, the deflection increased rapidly at some load and the deflection of SN-gear was not different from that of nylon gear. This is because, the stiffener was not included up to the tip of nylon tooth, and the deflection of the part of addendum from pitch point increased. This can be surmised from the next experiment.

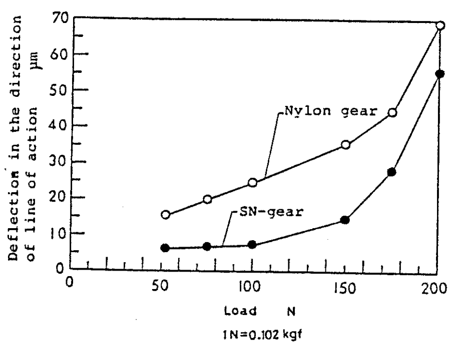


Fig.8 Deflection of tooth of SN-gear and nylon gear

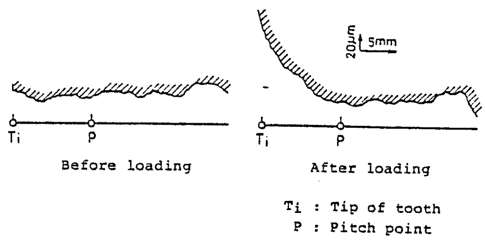


Fig.9 Tooth profile change of SN-gear under large load

Fig.9 shows that after the load 500 N(51 kgf) acted for 7 seconds, the load was removed and the tooth profile was measured by the base circle plate type tooth profile measuring apparatus. The tooth was plastically deformed at the part of the side of tooth face with the pitch point as the starting point.

4.2 Tooth profile

Fig.10 shows an example of the change of tooth profile in the course of operation of SN-gear. In this figure a line of $N_T=0$ shows a tooth profile before operation. A tooth profile for each operation is drawn at intervals of the quantity of abrasion from the line of $N_T=0$. Fig.11 shows the tooth profile of nylon gear which was measured under the same experimental conditions as the test of I-A-1 of Fig.10(a). The tooth profile of nylon gear, which meshed with the steel gear, largely changed from the starting point of action to near the pitch point and little changed at the side of addendum as shown in this figure.[5] Comparing this with Fig.10(a), the abrasion on the tooth profile was uniform in SN-gear. Fig.10(b) shows that the changes in the tooth profile of SN-gear and the tooth profile in the course of operation of this gear are nearly same as that of nylon gear in Fig.11. That is to say, the tooth profile change from the pitch point to the side of dedendum is larger than that from the pitch point to the side of addendum. The photograph in Fig.12 shows the state of tooth surface after the operation of 10^7 rotations in the test of I-B-1 as illustrated in Fig.10(b). The abnormal abrasion is denoted by a white line like the belt at the side of dedendum (a arrow).

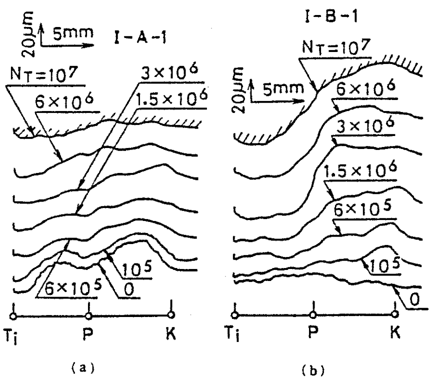


Fig.10 Tooth profile change of SN-gear in the course of operation

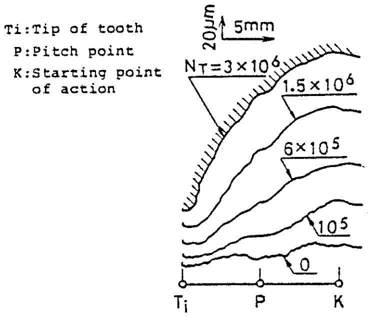


Fig.11 Tooth profile change of nylon gear in the course of operation

4.3 Improved SN-gear

SN-gear has a demerit that an abnormal abrasion occurs at the tooth flank like a nylon gear when the gear operates under a large torque because the stiffener is not included up to the tip of tooth. Therefore the gear was improved by making the dimension h, as shown in Fig.2, longer and including the stiffener up to the tip of tooth. Fig.13 shows the profile and the dimensions of tooth of an improved SN-gear. (The broken line shows the stiffener of SN-gear before improvement.) Fig.14 is a photograph showing an improved SN-gear after gear cutting. The top of a stiffener can be seen partly emerging at the tooth crest.

The test of an improved SN-gear was performed under the operational condition of I'-B group and II'-B group in Table 2 because we would like to confirm the abrasion at the part where the nylon of the tooth surface became thin. Fig.15 shows an

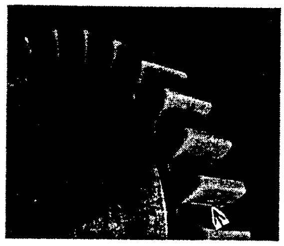


Fig.12 Abnormal abrasion of tooth flank of SN-gear

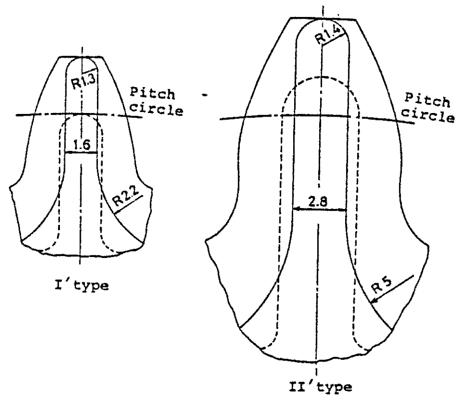


Fig.13 Dimension of stiffener at the tooth of improved SN-gear

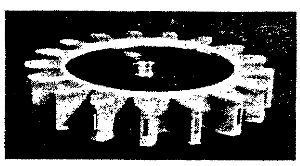


Fig.14 Improved SN-gear

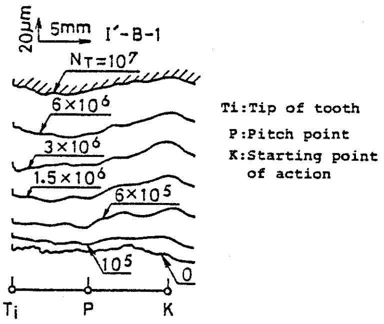


Fig.15 Tooth profile change of improved SN-gear in the course of operation

example of tooth profile change in this case. The abrasion on the tooth profile of an improved SN-gear, was almost uniform. Therefore the difference of pressure angle was small. And as enough nylon of tooth crest remained, the gear could be operated for a long time after that.

4.4 Noise

The noise of SN-gear was measured and compared with that of nylon gear. It was feared that the noise of SN-gear would be larger than that of nylon gear because the core of tooth and the gear body were made of carbon steel. Fig.16 shows an example of measured results. This is the measured results just before the end of operation of $N_T=1.5 \times 10^6$ rotations in II-A-1, I-A-2 and II-A-3. The generated noise of nylon gear sounded like "ZA,ZA" and that of SN-gear did like "SU ". This difference was illustrated by the results of frequency analysis in Fig.16. At the low frequency band under near 1 kHz, the sound pressure level of SN-gear, which had not a noise of "ZA,ZA", became low. But at high speed rotations, like 1500 rpm, the sound pressure level of high frequency band in SN-gear was higher than that in nylon gear. This is a demerit of SN-gear. But when two carbon steel gears meshed with each other and operated at the same conditions of this experiment, the sound pressure level of high frequency band over 2 kHz exceeded[4] 85 dB. Therefore comparing them with each other, the noise of SN-gear is not likely to raise a problem.

4.5 Temperature of tooth

Fig.17 shows the tooth temperature of a nylon gear and an SN-gear. The lower limit temperature in each experiment is an average room temperature in this 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.

The tooth temperature, which was measured like this, was not the correct tooth surface temperature. But the tooth surface temperature of SN-gear was lower than that of nylon gear as shown in Fig.17.

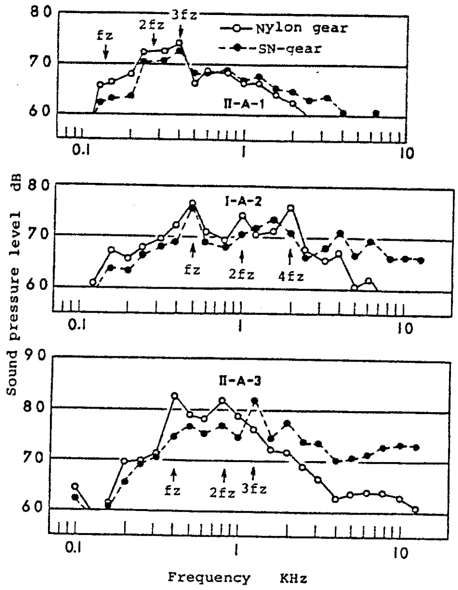


Fig.16 Comparison of the noise between SN-gear and nylon gear

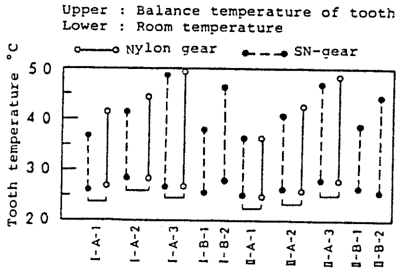


Fig.17 Comparison of the tooth surface temperature between SN-gear and nylon gear

5. Conclusions

As the means for preventing the tooth profile change of a nylon gear, which meshed with a steel gear, in this report, a nylon gear was designed, which included a stiffener of nylon tooth in the core of a nylon tooth and had small deflection.(The nylon gear was called SN-gear.) The operation (no lubricant operation) test of the gear was performed with the following results.

(1) The operation life of SN-gear was longer than that of nylon gear. The nylon gear, whose specification was used in this experiment, could not operate up to the total number of rotations 10^7 under the torque of 14.7 N.m(1.5 kgf.m). But SN-gear could operate up to $N_T=10^7$ under the torque of 20.58 N.m (2.1 kgf.m) and with no damage.

(2) The abrasion of SN-gear was smaller than that of nylon gear. Expression (1) gives the abrasion of SN-gear at $N_T=10^7$.

(3) In SN-gear the deflection of tooth was small and an abnormal abrasion at the tooth flank did not occur. Therefore the tooth profile (the pressure angle) did not largely change in the course

of operation, which was different from nylon gear.

(4) The sound pressure level of the generated sound of SN-gear was higher than that of nylon gear in the high frequency band over 1 kHz. But the sound pressure level did not exceed 85 dB as in the meshing of both carbon steel gear.

(Additional remark)

SN-gear has a large demerit that the weight of gear is large. The weight of type I nylon gear in this experiment is about 70 g and type II nylon gear is about 61g. But the weight of type I SN-gear is about 380 g and type II SN-gear is about 302 g. The next subjects of study will be the weight reduction of SN-gear and the theoretical selection of the dimension of stiffener.

(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.

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