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Investigation about the Strength of Plastic Gears

(1st. The Strength of Nylon Gears which have Counter-crowning)*

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Experimental studies to improve the load carrying capacity of plastic gears are presented. In the first place, the load test of nylon gear, which have the same cutting as steel gears, is tried and the limit value of power-transmission and the distribution of temperatures which rise under no lubricant are examined. In the next place, after the consideration of the temperature distribution in gear tooth, the load test of nylon gears which are cut with counter-crowning is tried. It is confirmed that these gears are able to be used for power-transmission under limited conditions.

1. Introduction

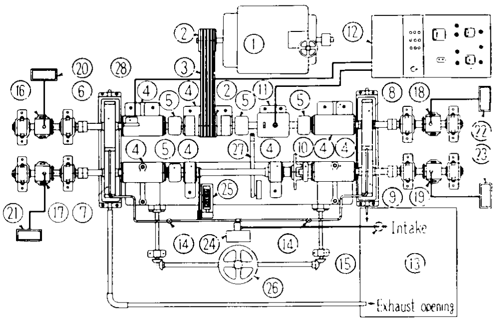
Plastic gears are usually not used for power transmission now because of a problem in their resistance to heat. These gears are generally used for the transmission of rotational motion. Partly these gears are used for power transmission, but they are put to discontinuous operations which are very short with very long time in pause. While plastic gears have a problem in their resistance to heat, they have some advantages that they are light, less noisy and self-lubricating. These gears will be useful in many machines for power transmission if the problem concerning power transmission can be overcome.

This study is done to utilize these advantages of plastic gears. In the first place, a load test of a nylon gear, which was meshed with a steel gear, was tried. And the operational ultimate strength of nylon gears for power transmission was confirmed and the temperature of teeth and state of breakage were investigated. Then it was confirmed that nylon gears were not able to operate under no lubrication except in an extremely light load operation, and temperature of tooth was higher at the center of face width than at the side of gear tooth.

In the next place, load test of a nylon gear with counter-crowning, which was reversed to normal crownings in usual steel gears, was tried. Counter-crowning was provided at the center of face width of nylon gear considering thermal expansion of nylon, because tooth temperature varies with the position along face width. Then the strength of nylon gear tooth was improved with the amount of counter-crowning and it is expected that nylon gears may be used for power transmission for a given range of powers. This paper will discuss the experimental results and indicate the problems which should be settled when nylon gears are to be used for power transmission.

2. Experimental apparatus and method

2.1 Fig. 1 indicates a power circulating gear testing machine. The power is supplied to the machine through ① speed controlled motor, ② v-belt wheel and ③ v-belt. The load is applied by ⑩ torsional load coupling. The load value is measured by a torque meter on ⑫ control box through ⑪ torque pick-up. ⑯ ∿ ⑲ slip rings and ⑳ ∿ ㉓ thermo-



① motor, ② V-belt wheel, ③ V-belt
④ bearing, ⑤ chain coupling,
⑥~⑨ testing gears and gears for circulating, ⑩ torsional load coupling
⑪ torque pick-up, ⑫ control box
⑬ oil tank, ⑭ oil control valve
⑮ filter, ⑯~⑲ slip ring,
⑳~㉓ thermoelectric thermometer
㉔ oil pump, ㉕ revolution counter
㉖ center distance control wheel
㉗ center distance indicate board
㉘ vibroswitch

Fig. 1 Gear testing machine and measuring equipment

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electric thermometers are used to measure the temperature of gear teeth in the nylon gear and steel gear. Center distance is variable from 190mm to 300mm by a center distance adjusting wheel.

2.2 Table 1 gives specifications of the test gear and mating gear. Fig. 2 gives their forms. Nylon gear was cut by hobbing and its backlash was set by increasing the center distance. Center distance was increased by 0.2∿0.9mm in nylon gears which had no counter-crowning (these gears are called (A) nylon gears after this) and in nylon gears which had counter-crowning, center distance was increased by 0.6mm (these gears are called (B) nylon gears after this). Both (A) and (B) gears were cut to grade of JIS-4.

Table 2 indicates mechanical and thermal characteristics of nylon materials used for this experiment.(1) In this investigation nylon gears were used mostly as driving gear, and partly as driven gear.

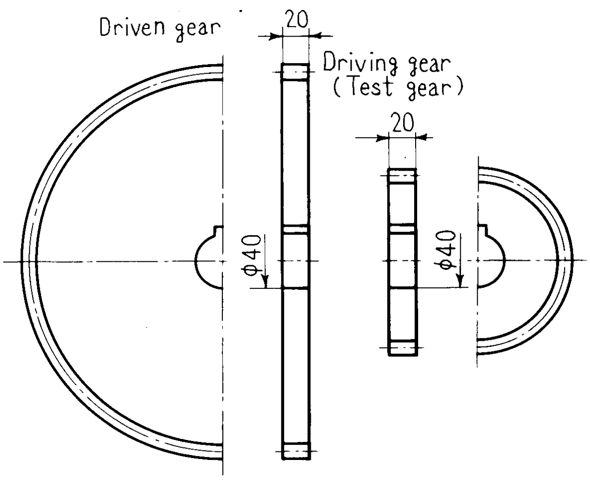

Fig. 2 Form of test gears

Table 1 Specification of test gears

	Driving gear	Driven gear
Module	5	
Pressure angle of reference	20°	
Number of tooth	34	57
Addendum modification coefficient	0	0
Diameter of pitch circle of reference	170	285
Diameter of top circle	180	295
Coefficient of top clearance	0.25	
Materials	Nylon	SNC21
Gear cutting	Hobbed	Hobbed and ground
Heat treatment		Cement quenching(H_{RC}52)
Accuracy	Grade JIS-4	Grade JIS-2

Table 2 Mechanical and thermal characteristics of nylon

Mechanical characteristics (23°C)	Specific gravity	Tensile strength (kg/mm^2)	Compressive strength (kg/mm^2)	Tensile elastic modulus (x10^3kg/cm^2)	Bending strength (kg/mm^2)
	1.15 ~ 1.17	770 ~ 980	980 ~ 1050	24.5 ~ 31.5	980 ~ 1120
Thermal characteristics	Thermal conductivity (kcal/m hr °C)	Coefficient of thermal expansion (/°C)	Specific heat (cal/°C gr)	Heat resisting temperature (°C) (long time)	
	2.0x10^{-5}	9.0x10^{-5}	0.4	121∿149 °C	

2.3 (A) nylon gears were examined on two conditions of lubrication, i.e., no lubrication and oil lubrication. Table 3 gives properties of lubricating oil. Oil was supplied to the gear by forced-feed lubrication and supplied to the gear teeth just before contact.

2.4 Tooth temperature was measured as follows. Thermocouple was made of alumel-chromel. Fig. 3 shows the plugged position of thermocouple in a gear tooth. The tooth was bored from the side of tooth to the center of face width and it was 1.2mm in diameter. The temperature was measured through a slip ring. Temperature at the side of tooth was measured by another thermocouple bonded by adhesive at the pitch circle on the side of tooth. The temperature was measured also by the "micro temperature indicating label".

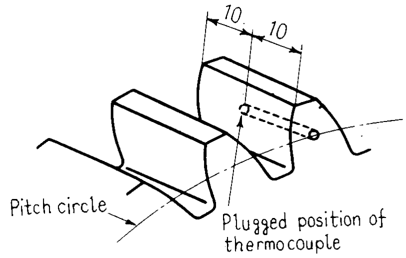

Fig. 3 Plugged position of thermocouple

2.5 Table 4 gives test conditions of (A) nylon gear and Table 5 gives those of (B) nylon gear.

Table 3 Properties of lubricating oils

Type		Gear oil 2-4
Specific gravity (15/4°C)		0.8770
Viscosity (cts)	17.8°C	60
	98.9°C	7.5
Viscosity index		98

Quantity of oils:1.04 (l/min)

Table 4 Test condition of gears which have no counter-crowning

Tooth surface load per unit face width (kg/mm)	0.94, 1.25, 1.88, 2.81 4.69, 6.26, 7.83, 9.71
Circumferential speed of pitch circle	4.45, 7.50, 11.57, 12.90

Table 5 Load test results of nylon gears which have Counter-crowning

No. of gear	Torque (Kg-m)	Quantity of Counter-crowning (μm)	Total number of rotations (Integrated number of rotations)	Breakage and crack of tooth
[1]	9.5	76	$5x10^5$	Breakage
[2]	9.0	76	50 "	Crack
[3]	8.0	70	100 "	None
[4]	9.0	53	50 "	Breakage
[5]	7.0	52	100 "	None
[6]	7.0	40	60 "	Crack
[7]	4.5	40	100 "	None
[8]	4.5	38	100 "	None
[9]	8.0	32	70 "	Crack
[10]	5.5	30	100 "	None
[11]	4.5	24	100 "	None
[12]	6.5	24	50 "	Crack
[13]	4.5	16	80 "	Crack
[14]	3.5	16	100 "	None
[15]	3.5	12	80 "	Crack
[16]	3.0	10	85 "	Crack
[17]	2.5	4	100 "	None
[18]	2.0	5	100 "	None
[19]	1.5	3	100 "	None

3. Results and discussion of load test of (A) nylon gear

Fig. 4 shows the relation between PV value and N_T obtained from results of load test of (A) nylon gear [P is normal tooth load per unit face width (kg/mm), V is circumferential speed at pitch circle (m/s), N_T is total number of rotations until breakage or seizure of tooth surface (Integrated number of rotations)].

In Fig. 4 N_T at the breakage of tooth lies near $N_T=5\times10^5$ regardless of PV value. This is due to the difference of the condition of stopping, some tests were stopped after perfect breakage of tooth and the others were stopped after a whitened crack occurred at the tooth, and so on. Nylon gears which seized at $PV \doteq 20$ were damaged a little. In the operation with lubrication, gear tooth was not damaged at PV=112.3. But in the operation without lubrication, nylon gear could not be operated to 10^7 rotation at $PV \doteq 14.5$ and over. Thus it was confirmed that nylon gear was not able to be used for power transmission under no lubrication.

3.1 Damage state and damage position of gear tooth

In no lubricating operation at $N_T=1.6\times10^4$ and under the lowest PV value, a projection appeared in the direction of face width on the tooth and at the position twice the module from addendum circle. This projection is a melted nylon material and its width is about 0.3mm (Photo. 1). This projection did not spread on the tooth surface up to $N_T=10^7$ when PV value is small. But when PV value increases, the projection spread toward pitch point (Photo. 2). This is due to the fact that at those positions the sliding speed is large and the temperature reaches the melting point of nylon materials. At $PV \doteq 38$ and over, a projection due to seizure occurred too, but gear tooth broke before tooth surface seized perfectly. When tooth surface seizes perfectly because PV value exceeds a limit value, P value instead of V value dominates PV value. In this experiment, seizure occurred at V=7.5m/s, P=7.83kg/mm, 9.26kg/mm, 4.69kg/mm. A gear tooth breaks when PV value increases with an increase in V value, not P value. In this experiment, tooth broke at V=11.57m/s, 12.90m/s, P=4.67kg/mm, 2.81kg/mm (Photo. 3). Gear tooth broke near the pitch point, Fig. 5. The radius of pitch circle of test gears was 85mm. But gear tooth broke at a point slightly outside of pitch circle because center distance was increased. It is believed that the reason why the nylon gear tooth breaks near the pitch point is that the elasticity of the material decreases largely due to a temperature rise there. The temperature distribution in nylon gear teeth is already reported by Takanashi(2) et al.

The crack of tooth occurred at the center of face width at first. (Photo.4) As heat radiation was relatively not restrained at both sides of tooth, temperature rise was low there. But at the center of tooth, as heat radiation was poor, the temperature there was higher than that at the side of tooth (see Fig.6). Then thermal expansion at the center of tooth was larger than that at the side of tooth and the load distribution became severe there. Then a crack occurred at that position. Considering these facts, a new method of crowning the nylon gear tooth has been developed, that is, a crowning reversed to normal crowning in steel gears, so that this tooth form becomes normal when tooth temperature rises in operation.

3.2 Temperature of tooth

Fig. 7 and Fig. 8 show two examples of temperature rises in steel gear and

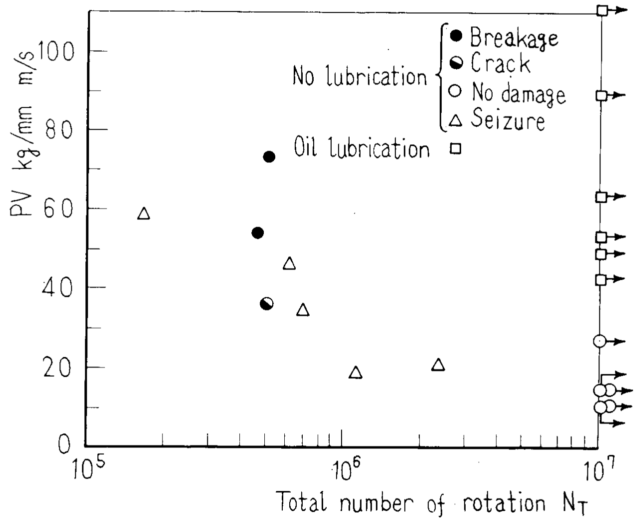

Fig. 4 Load testing results of nylon gears which have no counter-crowning

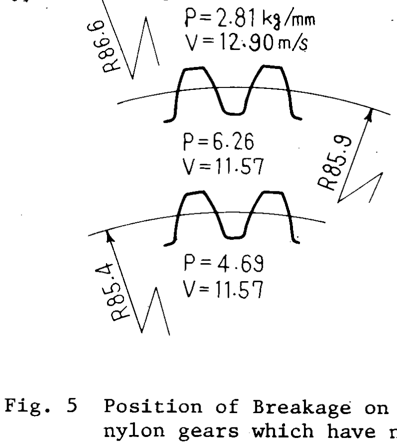

Fig. 5 Position of Breakage on nylon gears which have no counter-crowning

nylon gear. Fig. 7 is a slight seizure and Fig. 8 is a breakage of gear tooth. Comparing between steel gear and nylon gear, owing to the difference of thermal conductivity between them, the generated heat is transmitted to steel gear at first and the temperature of nylon gear tooth rises a little. When the heat ate freely from steel gear, both temperatures of steel gear and nylon gear rise with a constant difference between them. But when tooth load is large, radiation of steel gear reaches a limit in a short time as the generated heat is large. When radiation from steel gear reaches the limit, the generated heat is transmitted to nylon gear and the temperature of nylon gear tooth rises rapidly. Then temperatures of both gears approach each other. In this condition, Fig. 8, both temperatures of steel gear and nylon gear rise rapidly and then tooth of nylon gear breaks.

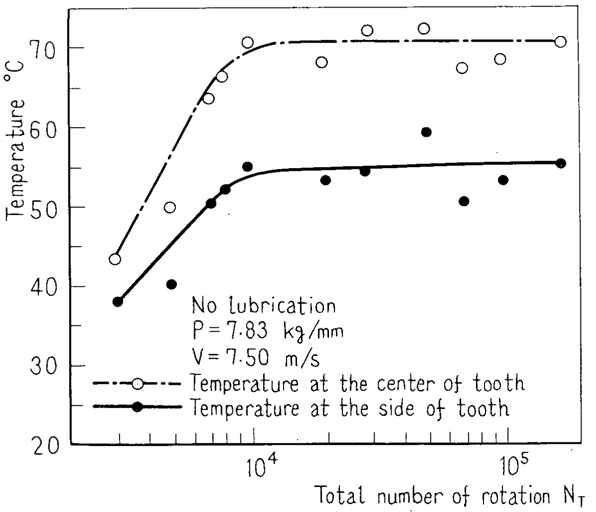

Fig. 6 Difference of nylon gear's tooth temperature at each position of face width

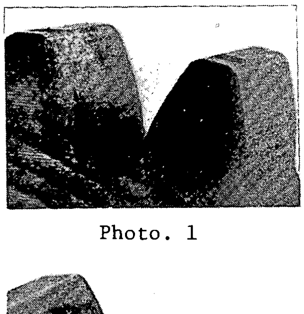

Photo. 1

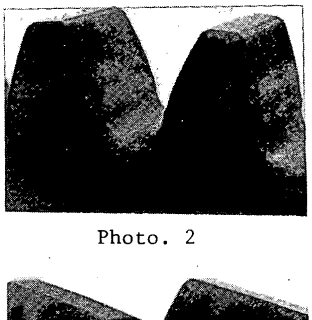

Photo. 2

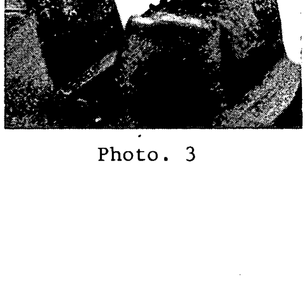

Photo. 3

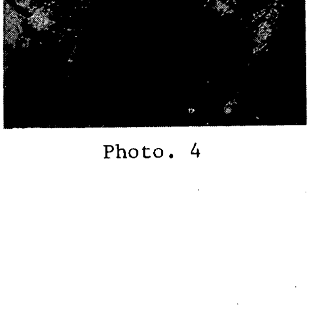

Photo. 4

4. Results and discussion of load test of (B) nylon gear

Temperature of tooth of nylon gear varies with the position along the face width considerably, see Fig. 6. Variation in temperature of tooth is analyzed and the amount of counter-crowning C defined by Fig. 9 was computed. Then the counter-crowning was given to each nylon gear, see Table 5, and load test was done on a trial and error basis. Results are summarized in Table 5. Circumferential speed at pitch circle V is 12.02m/s in each test of this table. As the amount of counter-crowning given to gears [17], [18], [19] is 5μm or less and these values are equal to or less than the roughness of tooth surface, it is not possible to prove clearly that the counter-crowning is effective in these gears.

Fig. 10 illustrates the relation between torque and the amount of counter-

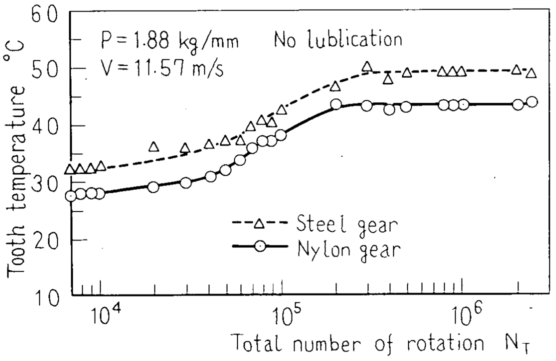

Fig. 7 An example of temperature rise in nylon gear (slightly seized)

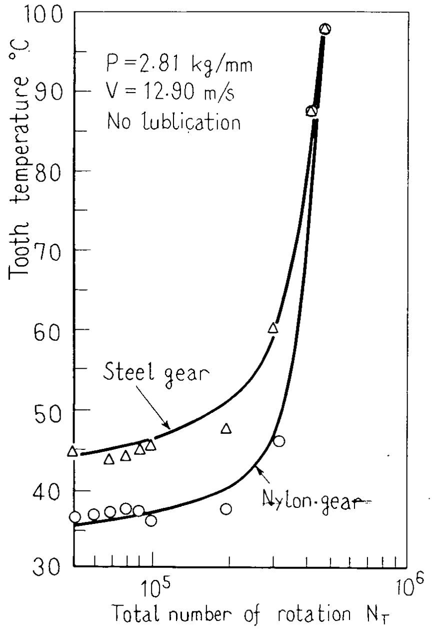

Fig. 8 An example of temperature rise in nylon gear (broken at gear tooth)

crowning. From this figure it is seen that when the amount of counter-crowning is increased, large torque is able to be transmitted. But it must be noted that the whole tooth surface does not contact the tooth surface of steel gear if the amount of counter-crowning is too much for a torque. In Fig. 10 if the amount of counter-crowning is 70μm, torque of 8.0kg·m can be carried. Converted to equivalent Hertz-stress in steel, it becomes 22.48kg/mm^2, see Table 6. This stress value approaches the strength of steel gear with no heat treatment. It is believed that if nylon gears have a strength of this degree, they are able to used for power transmission.

4.1 Damage state and damage position of gear tooth

Damage state of tooth of (B) nylon gear is the same as that of (A) nylon gear. But in (B) nylon gear seizure did not occur at all. Under no lubricant and large load on the tooth of (A) nylon gear, gear tooth was damaged in a very short time and it was not possible to observe the state of tooth surface. But in (B) nylon gear, a hollow was generated on the tooth surface, see Fig. 11. This hollow became larger when tooth load and total number of rotations were increased. Denoting the distance from the center of gear to the hollow on the tooth surface

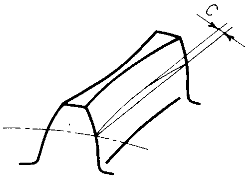

Fig. 9 Counter-crowning of nylon gear

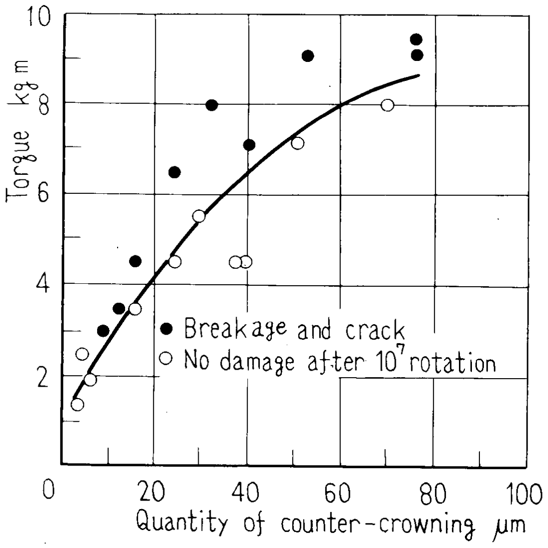

Fig. 10 Relation between torque and the amount of counter-crowning of nylon gear which has counter-crowning

Table 6 Steel equivalent Hertz-stress in nylon gear

Torque (Kg-m)	Steel equivalent Hertz-stress (Kg/mm^2)
10	25.13
8	22.48
6	19.47
4	15.90
2	11.24

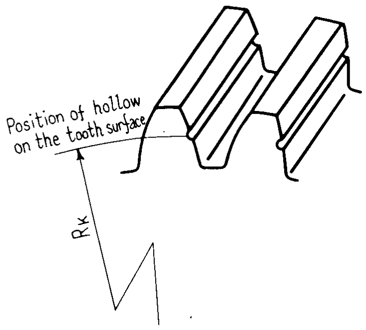

Fig. 11 Hollow on the tooth surface of nylon gear

Table 7 Position of hollow on the tooth surface

No. of gear	Distance from center of gear to hollow on the tooth surface R_K (mm)
[2]	84.4
[3]	85.5
[4]	85.4
[5]	85.6
[6]	85.6
[7]	85.2
[8]	85.0
[9]	85.4
[10]	85.0
[11]	84.6
[12]	85.5
[13]	85.6
[14]	85.3
[15]	85.6
[16]	85.6
[17]	85.6
[18]	85.4
[19]	85.6

with R_k, the values of R_k are given in Table 7. This hollow occurred near the pitch point (in the experiment center distance is increased by 0.6mm). When tooth load is large and tooth breaks, a crack occurs at this position at first. This position is located near the break position of (A) nylon gear. It is difficult to find any references which report that a hollow occurred on the tooth surface in operation of nylon gears. In this experiment, the process of a hollow growing on the tooth of nylon gear was taken in a photograph, Photo.5. Photo.5 shows an experiment at gear number [6]. The number of rotations, at which a hollow occurred on the tooth, was about $N_T=3.5x10^5$. The reason why the hollow occurs near the pitch point of tooth surface is speculated as follows. In this experiment the sliding of tooth is such that it takes place away from the pitch point. Then on the tooth surface, a kind of plastic flow is caused in a different direction from the pitch point. At this time, high temperature occurs near the pitch point of nylon gear and elasticity of the material decreases. Then tooth is going to be torn off. After the tooth is torn off over and over again, a hollow appears on the tooth. In order to confirm this theory, a load test was done under the following condition in this study. Gear dimensions are shown in Table 1 except that number of teeth of nylon gear is 57 and number of teeth of steel gear is 34. A nylon gear was used as driven gear and circumferential speed was 12.02m/s. When the amount of counter-crowning was 36 40μm under several loads, no hollow appeared on teeth of nylon gear. Load test was also done using gears with the same specifications shown in Table 1 at speed-up mode; a steel gear was taken as a driving gear and a nylon gear as a driven gear. No hollow appeared on the tooth surface of the nylon

(a) N_T = 24,400 (b) N_T = 150,000 (c) N_T = 300,000 (d) N_T = 1,100,000 (e) N_T = 5,600,000 (f) N_T = 6,000,000

Explanation of photograph
(○ : observed gear)

(a) Addendum of tooth is black because "Komyotan" remains. And "Komyotan" remains because temperature of tooth do not rise at the first time and addendum of tooth do not contact mate gear. "Komyotan" is a kind of paint for observation of gear contact pattern.

(b) "Komyotan" remains a little on the addendum of tooth at this time.

(c) "Komyotan" has been removed, but defects occurs such as abrasion dust. At this time, it is confirmed clearly that a hollow of tooth surface occurs.

(d), (e) It is confirmed that the hollow of tooth surface has grown.

(f) The operation was stopped as a crack occurred.

Photo. 5 Growing process of a hollow on a tooth of nylon gear

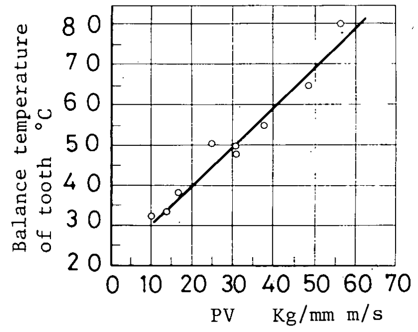

Fig. 12 Balance temperature of tooth

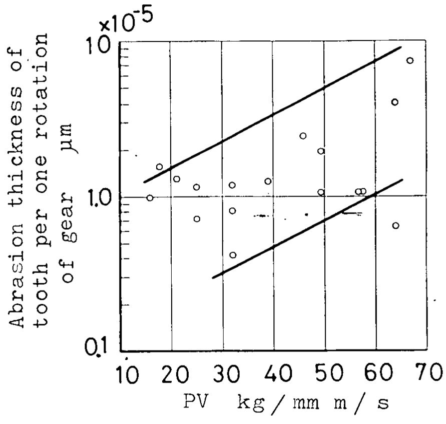

Fig. 13 Abrasion of nylon gear which has counter-crowning

gear in this case. It had been expected that tooth surface would swell towards the pitch point, but the swelling was not observed because tooth surface of the nylon gear was worn.

4.2 Temperature of tooth

There is the same tendency of temperature rise in (B) nylon gears and in (A) nylon gears. But (B) gear tooth did not break till those temperatures higher than the break temperature of (A) gear. Fig.12 shows the relation between a balance temperature and PV value.

In this figure P value is different from that in Fig. 4, and is a tangential load at pitch circle per unit face width of nylon gear. As nylon gear is weak under heat, the balance temperature of tooth in Fig. 12 is important when the strength of nylon gears is investigated. In this report only a tendency of balance temperature is shown and in the next report the relation between balance temperature of tooth and counter-crowning or strength of tooth will be shown.

4.3 Wear of tooth

Fig. 13 shows the wear of tooth of (B) nylon gear. This wear was measured at the side of tooth where the amount of counter-crowning was zero. The wear was measured after 20~24 hours from the end of each operation with each gear. P value denotes the tangential load at pitch circle per unit face width in this figure. The wear in Fig. 13 scatters just as in other wear tests, but it tends to lie between two lines drawn in the figure.

5. Conclusions

The following results have been obtained in the load test on nylon gears which have no counter-crowning and ones which have counter-crowning.

(1) As nylon gears have a problem in heat resistance, they can not be used for power transmission without oil lubrication.

(2) As the thermal conductivity is different between nylon gear and steel gear, tooth temperature of steel gear is higher than that of nylon gear when both gears contact. But when load on tooth surface is large, tooth temperatures of both gears become similar. This is because, tooth temperature of steel gear is high at the first stage of operation and then reaches a limit of radiation rapidly, then tooth temperature of nylon gear follows that of steel gear. As tooth temperatures of both gears continue to rise, tooth of nylon gear breaks.

(3) A tooth of nylon gear breaks near the pitch point, which differs from a tooth of steel gear. It is believed that the break position corresponds to a high temperature point of tooth of nylon gear where the elasticity of the material decreases.

(4) In nylon gears, tooth temperature varies with the position along face width considerably. The temperature at the center of tooth is higher than that at both sides of tooth. Then a crack of tooth occurs at the center of tooth at first.

(5) From the preceding, it is likely that the degree of thermal expansion varies with the position along face width. If nylon gears have counter-crowning with a hollow at the center of gear tooth, they are able to be used for power transmission in a limited period. Counter-crowning is reversed to normal crowning.

(6) After a long time of operation, a hollow occurs near the pitch point on the tooth of nylon gear. This phenomenon occurs only when nylon gear is used as a driving gear. It seems that a kind of plastic flow occurs according to sliding of tooth. Furthermore the crack of nylon gear which has counter-crowning occurs at this position.

(7) When nylon gears are to be used for power transmission practically, the following matters should be investigated and considered.

(7.1) The influence of module, gear ratio, and peripheral velocity at pitch circle on the strength of nylon gears should be considered.

(7.2) It is an advantage that the crack of tooth of nylon gear does not occur at deddendum of a tooth but occurs near the pitch point. But considering the strength of tooth, a thick part of tooth is stronger than a thin one. Then an employment of stub-teeth with less contact ratio should be examined.

(7.3) As nylon gears cost more than steel gears, they have to be manufactured at lower price, like molding and so on. In manufacture of nylon gears it would be an advantage that they do not require so high accuracy if the mating steel gears have enough accuracy.

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