Paper No. 84—0455

Development of Plastic Gears for Power Transmission*

(Various Methods of Lengthening the Life of Plastic Gears and Their Effect)

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The life of plastic gears is shortened when they are used at a high temperature because they become less strong and vary in the way they mesh with each other, causing them to be worn away at their root in an abnormal way. It is necessary for lengthening the life of plastic gears to take care not to generate heat in them and to keep them from rising in temperature due to radiating heat quickly. The present report deals with various methods designed for lengthening the life of plastic gears having form and dimensions adapted to given operating conditions and makes inquiries about whether the use of these methods can lengthen the life of plastic gears to a greater extent than expected at the time of designing.

Key Words: Gear, Plastic Gear, Nylon Gear, Tribology, Lubrication, Wear, Life of Gear.

1. Introduction

Plastic gears have many merits; silent running, no lubricated operation, light seizure, mass production etc.; but they have many demerits too; low-carrying capacity, low predictability of the life, low heat resistance etc.

In the previous report,(1) 62 experimental examples were selected from the past studies and sorted out. When the plastic gears of the same dimensions were operated under the same condition, the damage occurred in half of them and the total number of rotations up to the occurrence of the damage was $(2\sim3)\times10^6$ or 10^7. And half of them were not damaged. Ninety two % of the causes of damage were the breakage of tooth. The main cause was as follows. When the tooth temperature rose, the plastic was softened and the bending fatigue limit dropped.

The tooth temperature changes depending on the room temperature / the wear state of tooth profile, and the time when the temperature was measured just after the state of operation or the balance state. The fatigue limit and the modulus of longitudinal elasticity reduce to 65% when the temperature rises from 30 to 40°C. The breakage occurs accidentally when the tooth temperature changes and the loading state of the tooth and the allowable bending stress of tooth change. Therefore the temperature control is needed for the plastic gear so that the heat is not generated. It is necessary to radiate the generated heat smoothly. It is necessary to control the temperature rise and to reduce the variable width of temperature for the plastic gear.

In this report according to the above consideration, the life of plastic gear, whose tooth profile, dimension and operational condition were already decided, was stabilized and several methods, in which the life was made longer than the forecast life at design, were tried and their effect was examined and confirmed.

The examination was performed under the condition that the gear of one of the gear pair was a steel gear (S45C) and the room temperature was 20°C constantly. The material of plastic gear was MC nylon(2) the same as in the previous report. In this report the subscript p denotes the plastic and s the steel.

2. Several Methods of Lengthening the Life and Their Effect

The things to be improved are mentioned in the other report.(3) For example, a profile and a dimension of gear must be changed for the purpose of lengthening the operational life. In this paragraph the things in which a considerable effect can be gained with slight modification of machining, are treated. And in order not to repeat a same failure in future, examples of failares resulting from a contrivance any one can think up, are illustrated.

2.1 Method of lengthening the lifely, modifying the plastic gear

2.1.1 Cooling method

This method is as follows. A

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generated heat is cooled by the rotation of gear. In Fig. 1, the air at the side of gear body is blasted at the hole A under the space by the centrifugal force, and the air blows against the tooth surface through the hole B at the bottom of space. The tooth surface is thus cooled.

This centrifugal jet cooling method has an effect of lengthening the life of plastic gear. When the gear operated under the bending stress[1] at the pitch point of plastic gear σ=22.4 MPa (2.3 kgf/mm^2), the number of rotations n_p=1200 rpm, the tooth of usual circular plate type gear broke near the pitch point as shown in C of Fig. 1 at the total number of rotations $N_T \fallingdotseq (2\sim3)\times10^6$. But in the centrifugal jet cooling method the damage of tooth did not occur at $N_T \geq 10^7$. In the other method, in which the gear was cooled by a fan attached on the gear shaft, there was an effect of lengthening the life.[4]

2.1.2 Profile modification of plastic gear

As the tooth of plastic gear wears speedily and largely, there is not any effect when the profile modification is small. But the following method is effective. Figure 2(a) shows the state of tooth surface of plastic gear when gears fit each other. At the ellipse part of broken line the generated heat was less liable to radiate and the part swelled. The center of tooth surface wore as both sides of tooth were liable to deflect under loading. The tooth flank was scooped out by the tip of steel gear tooth and got worn. Therefore the tooth surface became fit as shown by the broken line.

As shown in the earlier report[4], the ellipse part of broken line became hot after the tooth surface of a steel gear was rubbed and the plastic softened. Then the tooth of plastic gear broke. If the tooth profile is modified to fit tooth profile, the breakage which has occurred at the first stage, can be prevented.

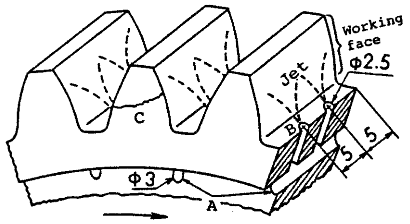
Figure 2(b) shows the tooth profile which has a counter-crowning (the center of face width is concave) and this tooth surface is similar to the fit tooth surface. With this modified tooth surface, under σ=22.4 MPa, n_p=1200 rpm, the gear was able to operate up to $N_T=10^7$. But with non-modified tooth profile, the gear tooth broke at $N_T=(2\sim3)\times10^6$. The strength of the plastic gear whose tooth had a counter-crowning, was already reported.[5]

Figure 2(c) shows the tooth profile, which was modified at the tooth flank. Because an abnormal wear occurred at the tooth flank. (The modified amount was 120 μm at the starting point of action). Under the same experimental conditions as Fig. 2(b), the gear was able to operate up to $N_T \fallingdotseq 8.7\times10^6$. The tooth profile was modified simply, because the tooth surface was less liable to reduce the fit tooth surface in Fig. 2(a). If the load does not concentrate at the part on the tooth surface before the tooth surface of plastic gear becomes fit, the damage, which occurs at the early stage of operation, can be prevented and the life is lengthened.

If the presence angle of plastic gear when the tooth is deflected by the load, is same as the pressure angle of steel gear, an abnormal wear at the tooth flank of the following tooth seems to be able to be prevented. But this is not the case for the following reasons. When the pressure angle of the steel gear and the plastic gear are α_c and α_{cp}, the gap c (Fig. 3) between this tooth and the following tooth becomes

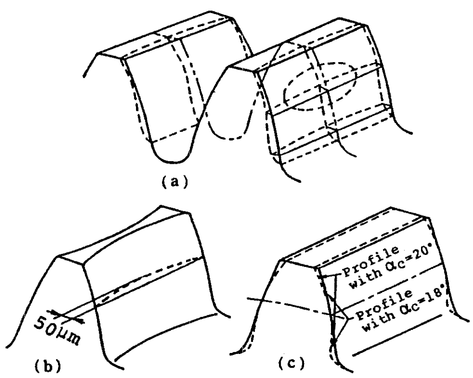
$$c=\pi m(\cos\alpha_{cp} - \cos\alpha_c) \quad \text{--------} \quad (1)$$

The pressure angle of the plastic gear α_{cp} was changed as shown in Fig. 3. Four kinds of plastic gears were prepared.



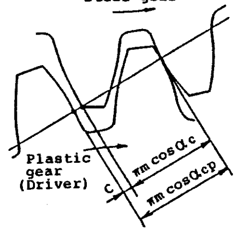
Module m = 5, Face width b = 15mm
Pressure angle α_c = 20°, Number of teeth [z_p = 17(Driver), z_s = 37

Fig. 1 Lengthening the life by the centrifugal jet cooling method



m=5, α_c=20°, z_p=17(Driver), z_s=37, b=20mm

Fig. 2 Profile modification, simulating the fitted tooth surface



m=5, z_p=17, z_s=37, b=10mm

α_{cp}(deg.)	20	19.5
c(mm)	0	0.046
N_T (rev.)	2.5×10^6	2.9×10^6
α_{cp}(deg.)	19	18
c(mm)	0.092	0.178
N_T (rev.)	2.4×10^6	0.33×10^6

Fig. 3 Intermeshing the gears, whose pressure angles are different

These plastic gears meshed with the steel gear, whose pressure angle α_c=20° under σ=22.4 MPa, n_p=1200 rpm. The results are shown in Fig. 3 as N_T.

When α_{cp}=18°, as the deflection in the acting direction of advance tooth was smaller than the gap c, the advance tooth meshed in one pair intermeshing from beginning to end. Therefore the life was shoft. When α_{cp}=19.5°, the life was the longest and the gear was able to operate up to N_T=2.9x10^6. In this case, c was 0.046 mm and the deflection of the advance tooth was from 0.05 to 0.127 mm. As the load of the following tooth was shared, the life seemed to lengthen. But as the tooth of plastic gear is liable to wear, the tooth flank is scooped out there after. Any great extension of life cannot be expected from this method.

2.2 Method of lengthening the life of plastic gear by modifying the mating metal gear.

2.2.1 Influence(6) of materials of mating metal gear.

As the material of mating gear of plastic gear, steel is used in many cases. The steel corrodes in the no lubricated operation. Therefore when the corrosion-proofness is needed, the material other than the steel must be selected. In this case, it is necessary to make clear what kind of metal is undesirable as the plastic gear material and how the wear of plastic gear changes due to the difference of metal materials.

Using a gear pair, which m=3, α_c=20°, Zs (number of teeth of metal gear)=30, Zp=60 (follower), b=10 mm, hobbed, gear accuracy JIS B 1702 Grade 4, wear test of the driven nylon gear was performed. As the materials of metal gears gray cast iron (FC20, H_B=200), stainless steel (SUS304, H_B=175), brass (BsB2, H_B=90), carbon steel for machine construction (S45C, H_B=185) were selected. The number of rotations of a driving metal gear was 1500 rpm and σ was 14.1 MPa (1.44 kgf/mm^2). The tooth surface roughness before operation of each metal gear was JIS ten points average roughness Rz=4.5∿5.5 μm.

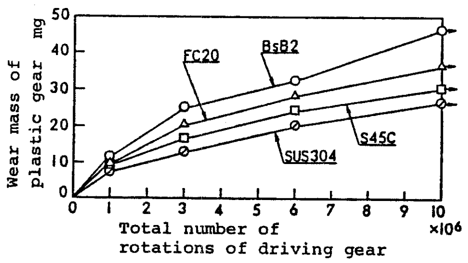


Fig. 4 Wear of the plastic gear depending on the material of metal gears

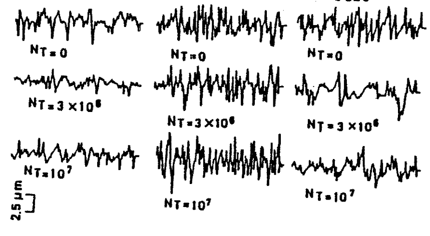


Fig. 5 Tooth surface roughness of metal gear

Figures 4 and 5 show the wear of nylon gear and the changes of tooth surface roughness of metal gear in the course of operation. When the nylon gear meshed with the gear of BsB2, the wear was the largest. Even in a meshed mating of plastic gear, the wear of soft brass gear was large. Worn powder cut into the plastic tooth surface, and this powder damaged the brass tooth surface. The rough brass tooth surface wore the plastic tooth surface too and the brass tooth surface was not smooth forever.

The projection of tooth surface in FC20 was less liable to wear because this material was as hard as H_B=200. Then the wear of plastic gear was large. In S45C, the tendency of wear was nearly the same as that of FC20. When the nylon gear meshed with the gear of SUS304, the wear was the smallest. As the stainless steel has suitable ductility and hardness, the wear of plastic tooth surface was small.

2.2.2 Influence(7) of tooth surface roughness of mating steel gear.

In the gear sliding contacts except the pitch point, the tooth surface roughness of mating steel gear ought to influence the wear of plastic gear. To confirm this phenomenon, a wear test was performed under the following conditions. A gear pair was same as in the experiment

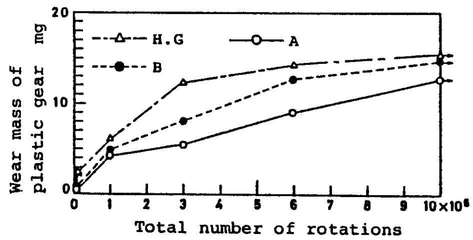


Fig. 6 Wear of the plastic gear due to the difference of the tooth surface roughness of the steel gear

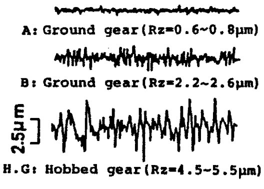


Fig. 7 Tooth surface roughness of mating steel gear.

of paragraph 2.2.1 and the nylon gear was a driving gear.

Figure 6 shows the results. In this figure, A denotes that the tooth surface of steel gear was precision ground as shown in Fig. 7, B denotes the normal grinding and H.G denotes the hobbed tooth surface. The smaller the tooth surface roughness of steel gear, the smaller the wear of plastic gear. But the amount of wear due to the precision ground tooth surface at $N_T=10^7$ was about 85 % of the amount of wear due to the hobbed tooth surface.

2.2.3 Method with profile modification of steel gear.

As shown in the previous report[7], in intermeshing the steel gear with the plastic gear (the plastic gear was a driving gear), a rotational delay occurred at the steel gear on account of a large deflection of plastic tooth of advance tooth. And the tooth flank of plastic tooth of the following tooth scooped out the tip of mating steel tooth (the abnormal wear at the tooth flank). If the tooth profile is modified from the worst loading point to the tip of tooth, this phenomenon can be prevented. The modified amount is an equivalent amount of the deflection of the plastic tooth of advance tooth.

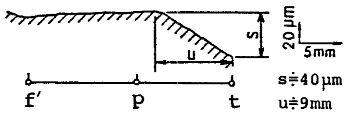
Figure 8 shows the modified tooth profile of steel gear in a gear pair, which is shown in the following specifications of this figure. This profile modification was performed from the tip of tooth to the position of u=9 mm, i.e. 40 μm. Figure 9(a) shows the wear of plastic gear (the gap of tooth profile recording diagram indicates the wear.) when the plastic gear meshed with the steel gear, which had a non-modified tooth profile under the operational conditions as shown under Fig. 8. Figure 9(b) shows the wear of the plastic gear when the plastic gear meshed with the steel gear whose tooth profile was modified. In Fig. 9(a) the wear depth of the tooth flank at $N_T=6\times10^6$ is 160 μm. Subtraction of wear depth of tooth face 50 μm from this wear depth 160 μm leaves 110 μm. Because the wear of tooth face is a natural wear. This 110 μm is nearly same as the calculated value 117 μm, which is the deflection of tooth in the direction of line of action when the normal load Pn=220.89 N acts on the ending point of a pair meshing (the worst loading point), as shown in the lower part of Fig. 8. If the tooth profile of the steel gear is modified by the amount of deflection 117 μm at the worst loading point of the plastic gear, the tooth of plastic gear must wear uniformly.

In Fig. 9(b), the subtraction of wear depth of tooth face 43 μm from the wear depth 113 μm leaves 70 μm. This wear is smaller than that of Fig. 9(a), that is by about 40 μm. When the tooth profile of steel gear is modified, the abnormal wear of tooth flank of plastic gear decreases and the life lengthens. As in the plastic gear the wear increases in the course of operation and the deflection of tooth of plastic gear changes largely due to the temperature, the amount of profile modification can not be set at a constant value.

2.2.4 Cooling method

The friction heat, caused by the sliding contact between the tooth surface of plastic gear and the tooth surface of steel gear, almost transmits to the steel gear because the heat conductivity of the plastic one is poor. Therefore the temperature of tooth surface of steel gear is higher than that of plastic gear in the course of operation, 5∿10°C. If the temperature of steel gear drops, the generated heat is liable to be absorbed by the steel gear and the temperature rise in the plastic gear is restrained and the life lengthens.

Figure 10 shows that the centrifugal jet cooling method (Fig. 1), which is effective to lengthen the life of the plastic gear applies to the steel gear too. When the rotation of gear is slow or the cooling is insufficient, a feathered fan may be fitted to the side of gear and the air may be forcibly blown into in the air entrance. The dimensions of gear pair

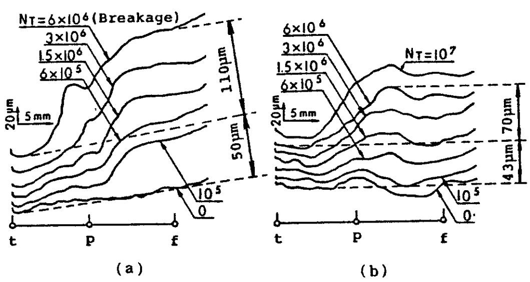


t:Tip of tooth, p:Pitch point,
f':End of action
$u=(\varepsilon-1)t_n$ (ε:Contact ratio, t_n: Normal pitch)

Specifications

$m=5$, $\alpha_c=20°$, $z_p=17$(Driver), $z_s=37$,
$n_p=1500$rpm, b=10mm,
σ=20.2MPa(2.1kgf/mm²)
Normal road P_n=220.89N(22.54kgf)

Fig. 8 Profile modification of steel gear and operational conditions



f:Starting point of action
Specifications are shown in Fig.8

Fig. 9 Wear of tooth of plastic gear under profile modification or no profile modification of steel gear.

as shown in Fig. 10 are same as those in Fig. 1. This gear was examined under the following conditions. The load increased over that of Fig. 1 and σ was 28.0 MPa (2.9 kgf/mm^2), which was 1.25 times as large as that of Fig. 1. The number of rotations n_p=1200 rpm. Then the temperature of the tooth surface was smaller than that of Fig. 1, i.e. 4°C and the gears could operate up to the total number of rotations $N_T=10^7$ and over.

2.3 Method of lengthening the life as a gear pair.

The object gears in this study are a plastic gear and a metal gear. We examined the lengthening of the life as a gear pair.

2.3.1 Use as a gear wheel.

In the gear pair of the pinion, whose number of teeth is Z_1 and the gear wheel, whose number of teeth is Z_2, when the gear wheel is a plastic gear, if the material cost is allowed to increase, the life seems to lengthen the number of teeth ratio i ($=Z_2/Z_1$) times as compared with use of pinion.

This is because the number of loadings of gear wheel is smaller than that of pinion, i. And as the cooling time when the time from the end of one meshing to the start of next meshing, lengthens i times, a drop in the mechanical strength of plastic material due to the temperature rise is prevented.

The gears were operated under the following conditions. The plastic gear was used at lower speed, when its number of teeth was 37 as shown in the specifications of Fig. 1. The steel gear could operate up to the total number of rotations (the total number of rotations at the side of driving gear) 7.9×10^6 (at that time the operation of gears was stopped as the pitting became large). This value was larger that the value, i.e. i=37/17 times the life $(2\sim3)\times10^6$ when the driving gear was a plastic gear. This is because the gear wheel was a plastic gear and this plastic gear was used as the driven gear, as shown in the following.

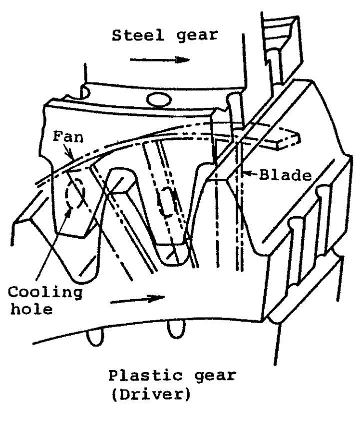


Fig. 10 Centrifugal jet cooling method with fan

2.3.2 Use as a driven gear

When the plastic gear is used as a driven gear, the tip of tooth of plastic gear, whose tooth is liable to bend at the starting point of action, meshes with the tooth flank of steel gear and then the impact due to the interference is relieved. As the direction of tooth action is from the side of tip and the side of root to the pitch point, the hollow, which is a possible cause of breakage, dose not occur. And as the tooth flank of plastic gear dose not push the tip of tooth of steel gear but pulls and hooks the tip, the abnormal wear of tooth flank must be small.

To confirm this subject, the state of wear of the plastic gear and the steel gear, whose gear ratio was 1:1 and which were used as driving and driven gears, was compared. Figure 11(a) shows the state of wear of plastic gear, which was used as a driven gear and Fig. 11(b) shows the state when it was used as a driving gear. Comparing both figures, the abnormal wear of tooth was large especially when the driving gear was a plastic gear. And the tooth temperature was higher by several degrees. It can be sensed by hearing how the noise from the driven gear (which was the plastic gear) can be abated. The plastic gear possesses many merits in the driven gear.

2.3.3 Method of lengthening the life through lubrication.

The plastic gear has a merit, in that it is self-lubricating. When the gears are lubricated, the sliding of tooth surface becomes smooth, the generated heat decreases and the life of gear lengthens 2 or 3 times. This is the effective method.

Figure 12(a) shows the state of wear of plastic gear when the operational conditions are as shown in this figure.

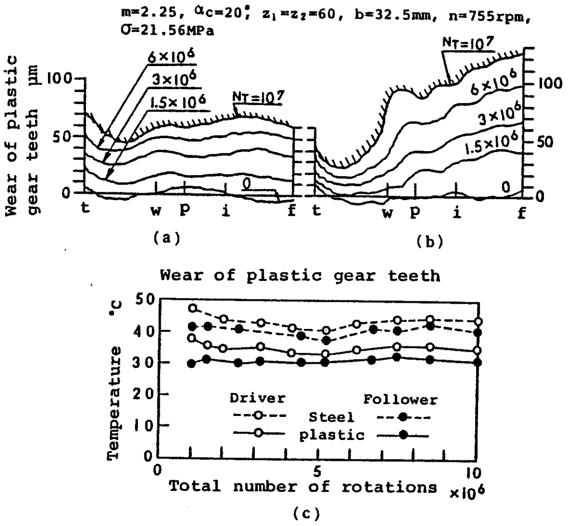


Fig. 11 Wear and temperature of tooth when the driven plastic gear and the driving gear are plastic ones.

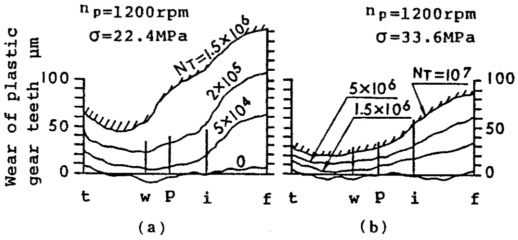
Gears were operated at the room temperature 20°C with no lubrication. The temperature of tooth surface exceeded 50°C at the end of operation and the tooth of plastic gear broke at $N_T=2.8\times10^6$. At that time the gear noise increased conspicuously.

Figure 12(b) shows the results under the following conditions. The same gear pair was housed in the gear box and the gear oil (Dephnis-pamulti68) of $10^{-3}m^3$ (1L) was stored at the bottom of box and the gear pair was splashed with the oil. In this case, anticipating that the life of plastic gear would lengthen, the load was increased so that the value of increased 50 % over that in Fig. 12(a).

In this oil lubrication, in spite of the load being increased the life lengthened over 10^7 of total number of rotations and the temperature of tooth surface was as low as 33°C. And the operation became quiet. Comparing Fig. 12 (a) with Fig. 12(b), the wear of tooth under oil lubrication and $N_T=10^7$, decreased below that under no lubrication and $N_T=2\times10^5$. In non-lubricated operation, when grease or vaseline was applied on the tooth of plastic gear until the plastic gear fitted, the gear fitting went smooth. When the tooth surface roughened in the course of non-lubricated operation, grease or vaseline was applied for a short time. Then the tooth surface became as smooth as in the first state.

2.4 Combined effect of various methods of lengthening the life.

When various methods of lengthening the life, which have been proposed until now, are used together, the following combined effect can not be expected. For example, if the method A of lengthening the life is used, the life lengthens 3 times over that when no method is used, and the life lengthens 2 times due to the method B of lengthening the life and the life lengthens 1.5 times due to the method c of lengthening the life. When these methods A, B, C are used at the same time, the life lengthens 3x2x1.5=9 times due to the combined effect or 3+2+1.5=6.5 times due to the added effect. About these subjects more study will be needed, but the life will surely lengthen over 3 times. Unless an epoch-making method of lenthening the life is discovered, any method of lengthening the life, which seems more effective, should be used.



m=5, α_c=20°, z_p=17(Driver), z_s=37, b=10mm

t:Tip, w:Worst point, p:Pitch point, i:Inner worst point, f:Starting point of action

Fig. 12 Wear of plastic gear under oil lubrication or no lubrication.

3. Conclusions

As the plastic gear is weak to heat, it is necessary to dissipate the generated heat and inhabit occurrence of abnormal wear at the tooth flank, which causes heat generation.

From this investigation, the following may be concluded about the effective methods of lengthening the life.

(1) A method where by a small hole was provided at the bottom land of the gear and air was blasted by the centrifugal force due to the rotation of gear to cool the tooth surface, was effective for the steel gear and the plastic gear.

(2) The tooth of plastic gear fitted after the center of the tooth in the direction of face width and the tooth flank in the direction of tooth depth wore. The profile modification, which simulated to this fitted tooth surface, was effective for the prevention of breakage of tooth, which occurred at the start of operation.

(3) The hardness of mating metal gear influenced the wear of tooth of plastic gear. The wear was small at H_B=160 180.

(4) The smaller the tooth surface roughness of mating steel gear, the smaller the wear of tooth of plastic gear. Although the tooth was ground, the wear did not decrease.

(5) When the tooth profile of steel gear was modified by the amount of deflection of tooth of plastic gear by the load, the abnormal wear at the tooth flank of plastic gear could be prevented.

(6) In a pair gear, when the plastic gear was a gear wheel, the method of lengthening the life of the plastic gear effective. Because the number of loadings of tooth decreased and the period of cooling extended.

(7) Intermeshing of the driven plastic gear was smoother than that of the driving plastic gear. And in the driven plastic gear, the abnormal wear of tooth flank decreased and the life lengthened.

(8) If the oil lubrication is allowed, the generation of the friction heat decreases and the life lengthens. When the tooth of plastic gear was fitted at the start of operation or when the tooth surface of plastic gear was roughened, grease or vaceline was

applied a little. This method was effective to lengthen the life.

(9) Even when the various methods of lengthening the life are used together, the combined effect and the added effect can not be expected. But any effective methods of lengthening the life should be used together so that the reliability of effect of lengthening the life can be increased.

We would like to thank Dr. T. Nishida, Assistant Professor of Nagasaki University and Nippon Poripenko Co., ltd. for his help with the experiments.

References

(1) Terashima, K., et al., Preprint of Japan Soc. Mech. Engrs. (in Japanese), (1985-4), No. 84-0454 B.

(2) Terashima, K., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), 50-449, C (1984), p.204.

(3) Terashima, K., et al., Preprint of Japan Soc. Mech. Engrs. (in Japanese), (1985-4), No. 84-0456 B.

(4) Terashima, K., et al., Preprint of Japan Soc. Mech. Engrs. (in Japanese), (1983) No. 830-8, p.124.

(5) Tsukamoto, N., Trans. Japan Soc. Mech. Engrs. (in Japanese), 45-391, C (1979), p.382.

(6) Tsukamoto, N., Preprint of Japan Soc. Mech. Engrs. (in Japanese), No. 820-10 (1982), p.144.

(7) Tsukamoto, N., Trans. Japan Soc. Mech. Engrs. (in Japanese), 49-447, C (1983), p.2048.