Long-life Gear Oils for Electric Railway Trains

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A long-life gear oil for electric railway trains was developed to reduce the workload and cost of gear unit maintenance. A semi-synthetic base oil, a mixture of polyalphaolefin (PAO) and highly purified mineral oil, was used in the developed gear oil in order to improve high temperature oxidation stability. The composition of additives was also modified to enhance oxidation stability. In an accelerated oxidation test (Indiana stirring oxidation test at 135 °C /96 hours), the developed gear oil demonstrated sufficient oxidation stability to enable an electric train to run 1,200,000 km without an oil change. Reliability at low temperatures was also shown to be better compared with existing gear oils, because the viscosity at low temperatures and the pour-point was reduced by virtue of the semi-synthetic base oil.

Keywords: gear oil, gear unit, maintenance, long-life, polyalphaolefin, high temperature oxidation stability

1. Introduction

Gear units on electric trains are lubricated using gear oil. The gear oil is used for lubricating not only the tooth face of pinion and gear, but also tapered roller bearings near each gear as shown in Fig.1.

Based on the current periodic inspection system in Japan, train gear oil is generally changed before reaching 600,000 km. If the gear oil has good durability and can reach 1,200,000 km i.e. twice the normal service cycle, then it can be expected that this type of oil would not require change at 600,000 km (Fig.2). Therefore, long-life gear oil has the potential of cutting the need to change gear oil by half, thereby reducing the cost and workload of electric railway train maintenance.

In this study, a long-life gear oil was developed with a serviceable life of 1,200,000 km on conventional line trains.

![Fig. 1  Lubricating points in the gear unit of an electric railway train](image)

Fig. 2 Reducing gear oil replacement by using long-life gear oil

2. Analysis of degradation factors and determination of target properties

2.1 Analysis of used current gear oil obtained from a car in service

For the determination of the target properties of the oil to be developed, used current gear oils sampled from the gearboxes of a car in service were analyzed. The samples of oil were used for 180,000~580,000 km on an electric commuter train gear unit. Kinematic viscosity at 100 °C was measured according to Japanese Industrial Standards (JIS) K 2283. Heptane insolubles were measured by using a method comparable to that given by the American Society for Testing and Materials (ASTM) D 893 procedure A, change of the solvent from pentane to heptane. Water
content was measured through Karl Fischer titration according to JIS K 2275. And the total acid number (TAN) was obtained by potentiometric titration method according to JIS K 2501. The results were compared with the control criterion value [1], proposed by Railway Technical Research Institute as an indication of the serviceability limit for lubricants, shown in Table 1.

As shown in Fig. 3 (a), (b), (c), and (d), increase in kinematic viscosity, heptane insolubles, water, and rise in TAN all satisfy control criterion value. However, a slight increase in TAN is observed around 400,000~600,000 km. The TAN of the gear oil decreases in the early stage of use due to the competition between the action of anti-oxidant additives and the consumption of additives containing the acid number, and rises following a decrease in anti-oxidant additives. Therefore, it is suggested that the current gear oil after 400,000~600,000 km is easily oxidizable because of the decrease in anti-oxidant additives. Furthermore, it is implicated from Fig. 3 (d) that the TAN increase exceeds the criterion value, 0.5 mgKOH/g increase from new oil, before the use for 1,200,000 km. Accordingly, it is recognized that oxidation resistance needs to improve to ensure long-life gear oil can be used for distances of 1,200,000 km without change.

2.2 Determination of the target properties of long-life gear oil

The target properties of long-life gear oil were determined and are shown in Table 2. As a result of used gear oil analysis, it was decided that oxidation stability had to be set better than for current gear oil. Moreover, the viscosity at low-temperature was set lower than the current gear oil as a countermeasure against defective lubrication due to viscosity increase in cold regions. Viscosity at high temperature was set at a level comparable with current gear oil requirements. The lubricating performance of long-life gear oil, e.g. load capacity, was set either equal to or better than the current gear oil.

3. Trial production of long-life gear oil and performance test of the developed long-life gear oil

3.1 Selection of base oil

Generally, the base oil of lubricating oils is classified into mineral oil and synthetic oil, i.e., oil made of petroleum distillates and made of chemical syntheses, respectively. Examples of synthetic oil include polyalphaolefins (PAOs), esters, ethers and silicones. As for the long-life

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### Table 1 Control criterion value for gear oil (conventional railway)

| Method                                      | Criterion value                                      |
|---------------------------------------------|------------------------------------------------------|
| Kinematic viscosity (100 ℃) (JIS K 2283)    | Inside ± 15 % change from new oil                    |
| Heptane insolubles (Comparable to ASTM D 893 procedure A) | Up to 1.0 %                                          |
| Water (JIS K 2275)                         | Up to 0.2 %                                          |
| Total acid number (TAN)(JIS K 2501)        | Up to 0.5 mgKOH/g increase from new oil             |

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Fig. 3 Analysis value of used current gear oils
gear oil, whereas the current gear oil uses mineral oil, PAOs were adopted as base oil because of their strong anti-
oxidation and viscosity index, and track record as a base oil 
for gear and axle roller bearing lubricant on Shinkansen 
vehicles [2,3]. In this long-life gear oil, PAOs synthesized 
with metallocene catalysts were used with a view to en
hancing low-temperature fluidity and reducing resistance 
to stirring. Nevertheless it is too costly to use base oil 
composed of only PAOs. Hence, semi-synthetic oil, which 
was produced by mixing PAOs with highly purified mineral 
oil to the extent that the high performance of PAOs is not 
spoilt, was used. Prototype long-life gear oil was developed 
using semi-synthetic base oil and testing oxidation stabili

3.2 Determination of test condition for estimating 
adoxidation stability

The oxidation stability of developed gear oil was tested 
by Indiana Stirring Oxidation Test (ISOT) according to JIS 
K 2514, the accelerating oxidation test for lubricant oils. 
The apparatus for ISOT is shown in Fig.4. Test oil tem
perature was set at 135 ℃.

The test time for the ISOT on the developed gear oil 
was determined from the total base number (TBN) of the 
current gear oil used in service. The TBN provides an 
indication of the degradation of gear oil, because the cur
rent gear oil contains basic additives and these additives 
are consumed as the gear oil degrades [4]. In this study, 
the TBN was measured using the perchloric acid titration 
method according to JIS K 2501.

The TBN of the current gear oil used in service de
creases to 1.4 mgKOH/g after 570,000 km, as shown in 
Fig.5 (a). On the other hand, it is estimated from the re
lation between the TBN and ISOT test time as shown in 
Fig.5 (b) that the TBN of the current gear oil decreases to 
1.4 mgKOH/g after 42-hour ISOT at 135 ℃. Accordingly it 
can be said that the current gear oil after 42-hour ISOT at 
135 ℃ degrades to the same extent as after use for 570,000 
km in service. Thus, the test time of ISOT was set at 96 
hours, which corresponds to use for 1,300,000 km, to simu
late degradation after 1,200,000 km or more.

3.3 Evaluation of the oxidation stability of the de
veloped long-life gear oil

Firstly, an ISOT (135 ℃, 96 hours) using “developed 
gear oil A,” composed of semi-synthetic oil as base oil and 
the same additives as in current gear oil, was carried out. 
Results showed that the TAN increase was smaller than

| Table 2 Target properties of long-life gear oil |
|-----------------------------------------------|
| Oxidation stability                          | As low as or below +0.5 mgKOH/g increase of TAN in deteriorated oil corresponds to 1,200,000 km used. |
| Viscosity                                     | Lower than current oil at low temperature. Same as current oil at high temperature (100 ℃). |
| Lubricating performance (load capacity, anti-wear) | Same as or better than current oil. |

![Fig. 4 Apparatus for ISOT](image)

![Fig. 5 Variation of the TBN of the current gear oil with oil degradation](image)
the current gear oil, shown in Fig.6. This implies that the oxidation stability improved by changing the base oil to semi-synthetic gear oil. However, the TAN increase of the developed gear oil A remained higher than the target value, 0.5 mgKOH/g. Thereby, the additive composition was reviewed producing “developed gear oil B,” containing a larger amount of detergent-dispersant additive than in A, which was then tested in the same way. The TAN increase in developed gear oil B decreased further than in A and achieved the target properties shown in Fig.7. Moreover, the TBN (corresponds to residual basic additives), kinematic viscosity and heptane insolubles of developed gear oil B after the ISOT showed more favorable conditions than for current gear oil. According to the results, it is confirmed that developed gear oil B has sufficient oxidation stability for 1,200,000 km.

### Fig. 6 TAN increase of the developed gear oil A after the ISOT (135 °C, 96 hours)

![Graph showing TAN increase of the developed gear oil A]  

#### (a) Last non-seizure load

![Graph showing last non-seizure load comparison]  

#### (b) Weld point

![Graph showing weld point comparison]

### Fig. 7 TAN increase of developed gear oil B after the ISOT (135 °C, 96 hours)

![Graph showing TAN increase of developed gear oil B]  

### 3.4 Evaluation of lubricating performance by the four-ball test

The extreme pressure properties and anti-wear properties of developed gear oil B were evaluated by using a four-ball test machine and comparing results with those for current gear oil.

The last non-seizure load (LNL) and the welding point (WP) were measured according to ASTM D 2783 as a load capacity test. As a result, the LNL of the developed gear oil B is larger than the current gear oil and the WP is the same, as shown in Fig.8.

Anti-wear properties were also estimated by a wear prevention characteristics test, ASTM D 4172. The wear track diameter of the developed gear oil is smaller than the current gear oil as shown in Fig.9.

Accordingly, it is estimated from the four-ball test that the extreme pressure properties and the anti-wear properties of the developed long-life gear oil B are as good as or better than those of existing gear oils.

### Fig. 8 LNL and WP of the developed gear oil B at the four-ball test

![Graph showing LNL and WP comparison]  

### Fig. 9 Wear scar diameter of the developed gear oil at the four-ball test

![Graph showing wear scar diameter comparison]
3.5 Evaluation of lubricating performance by the IAE gear oil test

The load capacity of the developed gear oil B was also tested using the Institute of Automobile Engineers (IAE) gear oil test, according to the method described in the Institute of Petroleum (IP) 166. The apparatus for the IAE gear test is shown in Fig.10. The rotations of the pinion and the test oil temperature were set at 8,000 rpm and 80 °C, respectively.

As shown in Fig.11, the scuffing load of the developed gear oil B on the IAE gear test was slightly larger than the current gear oil. Thus, it was confirmed that the load capacity of the developed gear oil B is as good as or better than the current gear oil, as was the case with the four-ball test.

![Fig. 10 Apparatus for the IAE gear test](image)

![Fig. 11 Scuffing load of the developed gear oil at the IAE gear test](image)

| Table 3 Properties of the developed long-life gear oil (developed gear oil B) |
|---------------------------------|---------------------------------|-------------------------------|
|                                | Target                          | Developed gear oil B          | Current gear oil              |
| Base oil                        | Semi-synthetic (mixture of PAO and mineral oil) | Semi-synthetic                 | Only mineral oil              |
| Kinematic viscosity (mm²/s)     | SAE80W90                        | 40 °C :103                    | 40 °C :158                    |
|                                | (JIS K 2283)                    | 100 °C :16.3                  | 100 °C :17.7                  |
| Viscosity index (-)             | ≥ 130                           | 171                           | 124                           |
| Pour point (°C) (JIS K 2269)    | ≤ -40                           | -47.5                         | -37.5                         |
| Oxidation stability test (JIS K 2514) | (ISOT 135 °C, 96hours) | Increase in total acid number (mgKOH/g) | ≤ +0.5 mgKOH/g |
|                                |                                | Increase in kinematic viscosity (100°C) (%) | ≤ Current gear oil |
|                                |                                | Total base number (mgKOH/g)    | > Current gear oil |
|                                |                                | Heptane insolubles (%)        | < Current gear oil |
| Four-ball test                  |                                 | ≥ Current gear oil             | 980                           |
| Extreme pressure properties (ASTM D 2783) |                       | ≥ Current gear oil             | 774                           |
| Last non-seizure load (N)       |                                 | ≥ Current gear oil             | 3097                          |
| Welding point (N)               |                                 | ≤ Current gear oil             | 3097                          |
| Wear prevention characteristics (ASTM D 4172) |                | ≤ Current gear oil             | 0.416                         |
| Wear scar diameter (mm)         |                                 | ≥ Current gear oil             | 0.437                         |
| IAE gear test (IP 166) 8000rpm, 80 °C | | ≥ Current gear oil             | 509.6                         |
| Scuffing load (N)               |                                 | ≤ Current gear oil             | 490.0                         |
| Sonic shear stability test (ASTM D 2603) |                              | ≤ Current gear oil             | 0.3                           |
| Decrease of kinematic viscosity (100 °C) (%) | | ≤ Current gear oil             | 2.4                           |
| Foaming characteristics test (JIS K 2518) |                       | at 24 °C (ml)                 | ≤ 100                         |
| at 93.5 °C (ml)                 |                                 | ≤ 100                         | 10                            |
| at 24 °C after 93.5 °C test (ml) |                                 | ≤ 100                         | 5                             |
3.6 Properties of the developed long-life gear oil

Properties of the developed long-life gear oil are shown in Table 3. In addition to oxidation stability, low temperature fluidity related properties were also improved compared with current gear oil, i.e. kinematic viscosity at 40 °C, viscosity index and pour point. Other properties, e.g., sonic shear stability, foaming characteristics etc., were within the target values.

4. Conclusion

Long-life gear oil with a service life capable of 1,200,000 km was developed to reduce the workloads and costs of gear unit maintenance. In order to enhance high temperature thermal oxidation stability, semi-synthetic oil, i.e., a mixture of PAOs and highly purified mineral oils was used as the base oil. In addition the amount of detergent-dispersant additives was increased in comparison to current gear oil. By means of the TAN obtained by ISOT (135 °C, 96 hours), it was confirmed that the developed gear oil has higher high temperature oxidation stability and satisfies target properties regarding the increase in TAN, validating its service life of 1,200,000 km. The developed gear oil also showed sufficient extreme pressure properties, antiwear properties and good low-temperature fluidity. Accordingly, the developed gear oil can be applied to cases where it is desirable to avoid oil change before 1,200,000 km.

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