



Development of Electric Vehicle Oils with High Energy Efficiency and Cooling Performance by Applying Novel Friction Modifier

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Abstract

Improving the efficiency of electric vehicle (EV) transmissions can help to extend the driving range of EVs, and the EV oil used in these transmissions plays an important role. In this study, in order to enhance energy efficiency, we examined the effects of lowering viscosity, traction, and friction in EV oil. While friction modifiers (FMs) have been widely used as friction reduction technologies in the field of tribology for many years, we previously developed a new FM that reduces friction in drive units. We found that a combination of lowering viscosity and using the developed FM was effective for better energy efficiency. The oil formulated with the developed FM improved efficiency

by approximately +0.8% to +0.9% compared to commercial EV oil.

EV oil also requires cooling performance. We assumed that reducing heat generation through friction reduction would improve cooling performance and examined the effect of lowering viscosity, traction, and friction. Consequently, it was found that a combination of lowering traction and applying the developed FM is effective for reduction in parasitic heat losses. We also examined durability, which is an issue when reducing viscosity. The results suggested that the oil formulated with the developed FM had good durability for gears and bearings. Thus, we succeeded in developing an ultra-low-viscosity EV oil that has excellent energy efficiency and high cooling performance.

Keywords

Lubricant, EV oil, Friction modifier, Low viscosity, Low traction, Low friction, Energy efficiency, Cooling

performance, Heat generation

Introduction

The achievement of carbon neutrality is regarded in many countries and regions as indispensable to preventing global warming and building a sustainable society, and many governments and companies have devoted their effort to reaching this goal.

One such trend in the automotive field is the technological development toward vehicle electrification. In particular, efforts to promote the adoption of battery electric vehicles (BEVs) are progressing, along with the development of e-axes—the drive systems for BEVs—and

the development of dedicated lubricants [electric vehicle (EV) oils] and related technologies [1–12].

In this study, we examined three challenges hindering the widespread adoption of BEVs that are related to the development of EV oils. The first challenge is in the limited driving range of EVs; a potential measure that can extend driving range is improving energy efficiency with EV oils. To date, a number of studies have looked into ways of lowering the viscosity not only of EV oils but also various drivetrain oils as means to improve fuel economy and energy efficiency [4–6, 13–15]. On the other hand, recent reports indicate that

excessive viscosity reduction can actually decrease efficiency, and effective methods for further improving energy efficiency have not yet been fully clarified [10–12].

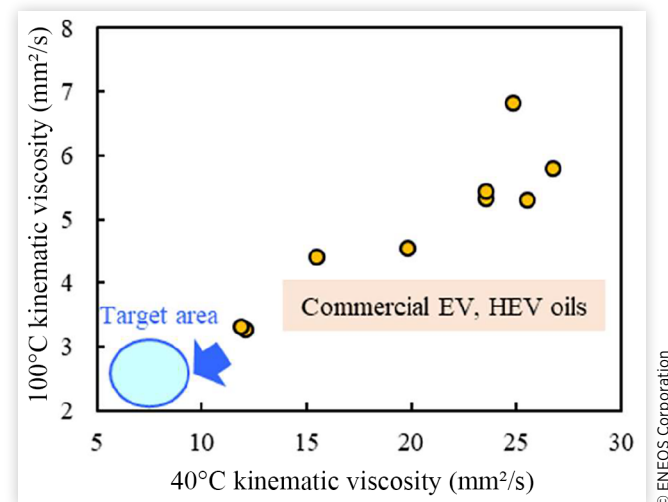
The second issue is the thermal management of the e-axis, including the motor. Operating the motor in high-temperature environments can cause problems such as short circuits and demagnetization, and if cooling is insufficient, key performance parameters of the motor—such as output density, durability, and driving range—can deteriorate rapidly [16]. Here, EV oils are being studied as means to improve cooling performance; approaches such as heat removal through heat transfer and suppression of heat generation at sliding parts have been studied [4, 15, 17–22]. With respect to heat transfer, it has been confirmed that lowering viscosity promotes the transition to turbulent flow in the fluid, which is effective for improving cooling performance [17–19]. Thus, clarifying the effects of viscosity reduction for the aforementioned energy efficiency improvement should also provide valuable insights for cooling performance. Furthermore, from the perspective of heat generation, it has been confirmed that reducing friction at sliding parts is effective [4, 15]. However, these findings regarding heat generation have been obtained only from tests using individual gears; more thorough investigations using actual transmission systems are needed.

The third issue is achieving both lower viscosity and sufficient component durability. While reducing viscosity raises concerns about decreased durability of components, particularly their fatigue life, balancing the trade-off between viscosity with durability has long been a challenge in the development of transmission oils, not only for EV oils [4–6, 13–15, 21].

To address these issues, the authors have previously reported that, by using a newly developed friction modifier (the developed FM) as a low-friction technology, it was possible to reduce the viscosity down to 8 mm²/s at 40°C, thereby achieving both improved energy efficiency and durability [23, 24]. On the other hand, the effects of low traction—which is considered effective for energy efficiency improvement—and viscosity levels below 8 mm²/s at 40°C were not investigated. Further studies on the lower viscosity range are thus important for achieving even greater energy efficiency and cooling performance.

In the study reported here, we expanded the scope of evaluation compared to previous reports, examining both energy efficiency and the durability of components. Additionally, we newly investigated the suppression of heat generation. First, we conducted efficiency tests under transient conditions using a reduction gear, with the aim of establishing methods for and further improving energy efficiency. In these tests, we expanded the range of target parameters, such as viscosity and traction, compared with previous studies and verified the effects of low viscosity, low traction, and low friction in EV oils. Next, we examined the impact of these factors on heat generation due to friction, again using a reduction gear. Finally, as part of the development of energy-saving EV oils, we evaluated the durability of bearings and gears—the main

FIGURE 1 Kinematic viscosity trends of commercial oils and targets.



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components of the e-axis reduction gear—using the low-viscosity EV oil that exhibited the best energy efficiency in our study.

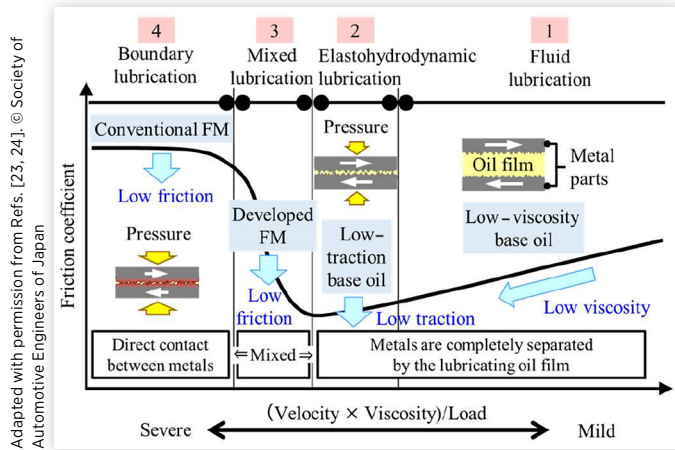
Through this series of evaluations, we achieved a significant reduction in viscosity down to 6 mm²/s at 40°C by applying the developed FM; this value is much lower than the viscosity of commercial EV oils, as shown in Figure 1. As a result, we developed an EV oil demonstrating superior energy efficiency and cooling performance.

Concept for Improving Energy Efficiency and Cooling Performance

Figure 2 illustrates, using a Stribeck curve, an example of methods and lubricant technologies for improving energy efficiency and enhancing cooling performance by suppressing frictional heat generation. Considering the lubrication regime suitable for energy efficiency and suppression of frictional heat generation, elastohydrodynamic lubrication (no. 2 in the figure) exhibits the lowest friction and is ideal if all parts can operate continuously within this regime. However, this is difficult to achieve in the case of an e-axis, which contains many sliding contacts across multiple parts and operates under a wide range of conditions. Therefore, lubricant technologies that reduce friction in each lubrication regime (nos. 1 to 4) are important.

In this paper, the term “low friction” refers exclusively to friction reduction in mixed lubrication (no. 3 in the figure) and boundary lubrication (no. 4), and it is distinguished from friction reduction in fluid lubrication, namely, lowering viscosity. Furthermore, fluid lubrication (no. 1), where a sufficient oil film is maintained between parts, is defined as a milder lubrication condition, whereas boundary lubrication, where the oil film becomes thin and metallic contact between parts occurs, is a more severe lubrication condition.

FIGURE 2 Effect of low viscosity, traction, and friction on Stribeck curve.



As shown in Figure 2, in fluid lubrication (1), lowering viscosity is effective in reducing both churning loss and oil film shear resistance. Therefore, as a lubricant technology, the use of low-viscosity base oils or reducing the amount of viscosity modifiers added is considered effective. It should be noted that, as described earlier, lowering viscosity has also been confirmed as an effective way of improving cooling performance by enhancing heat removal [17–19].

In elastohydrodynamic lubrication (2), the lubricant is compressed and its viscosity locally increases significantly due to the rise in pressure. The drag resistance generated during sliding in this lubrication is referred to as traction, and it is affected by the molecular structure of the base oil rather than additives. To reduce friction in this lubrication, it is effective to select low-traction base oils with a high linear chain ratio, which allow smooth movement under high-pressure conditions [4, 8, 14, 25].

In mixed lubrication (3) and boundary lubrication (4), friction increases significantly compared with fluid and elastohydrodynamic lubrication as a result of metallic contact between parts. For these lubrication regimes, it is considered effective to apply FMs that reduce metallic contact and friction.

Experimental Materials and Methods

Tested Oil

Table 1 shows an overview of the formulations of the test oils used in this study that are designed to evaluate friction reduction effects in each lubrication regime described in the previous section. Specifically, ten test oils were examined to clarify the effects of lowering viscosity (“Viscosity” in Table 1), lowering traction (“Traction”), and achieving lower friction (“Friction”). For comparison, a commercial EV oil with a kinematic viscosity of 12 mm²/s at 40°C—which is among the lowest-viscosity commercial products—was tested (Figure 1).

As shown in Table 1, to assess the effect of lowering viscosity, five test oils were formulated with kinematic viscosities at 40°C ranging from 17 mm²/s (maximum) to 6 mm²/s (minimum) (Samples A to E in the table). These test oils were formulated by adjusting only the base oil, without viscosity modifiers. All of the base oils used are high-performance base oils with lower traction than conventional base oils.

To evaluate the effect of traction, a test oil was formulated with conventional base oil at a viscosity of 12 mm²/s at 40°C. The effect of lowering traction was examined by comparing Samples B and B1 in the table.

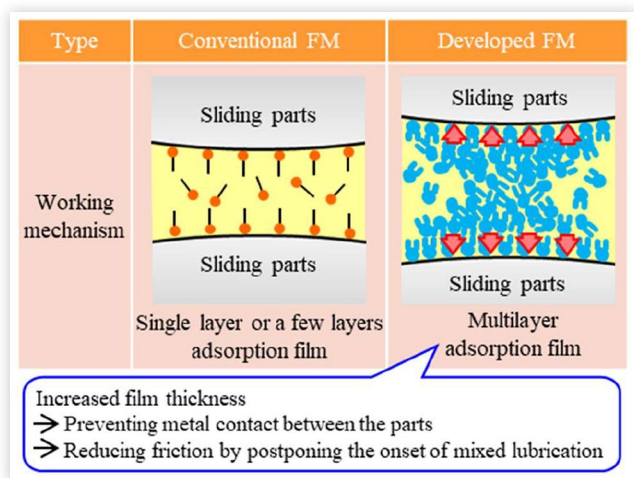
To evaluate the effect of lower friction, various FMs were added to Sample D (8 mm²/s at 40°C) to produce oils D1 to D3. For the developed FM, a version was also prepared by adding it to Sample E (6 mm²/s at 40°C) (Sample E1 in the table). As conventional FMs, ashless FM A (glyceryl monooleate) and polymer-type FM B (poly-methacrylate with adsorption groups)—both of which are widely used in lubricants—were selected [26, 27].

The developed FM consists mainly of components with an average molecular weight below 1000 and, from a structural perspective, it is classified as an ashless FM, like FM A. Figure 3 presents an image of the action of general ashless FM and the developed FM at sliding surfaces. FMs are believed to work by forming dense adsorption or reaction films on the surface, thereby reducing friction. Whereas conventional ashless FMs form

TABLE 1 Formulation overview of test samples.

Sample	Aim	Base oil	Additive	Additional FM	40°C KV* (mm²/s)
A	Viscosity	High-performance base oil	Newly developed additive formulation for EV oils	—	17
B				—	12
C				—	10
D				—	8
E				—	6
B1	Traction	Conventional base oil		—	12
D1	Friction	High-performance base oil		Developed FM	8
D2				Conventional FM A	8
D3				Conventional FM B	8
E1				Developed FM	6

* KV: Kinematic Viscosity

FIGURE 3 Estimated working mechanism of FMs.

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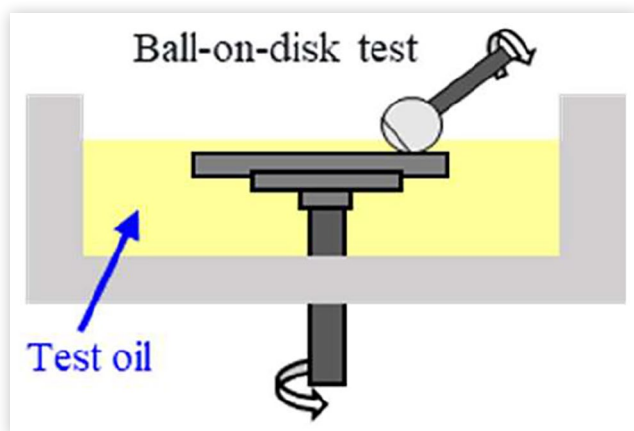
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single- or multiple-layer adsorption films, the developed FM is expected to form a thicker, multilayer adsorption film due to its multiple polar groups and stronger adsorption capability. The authors confirmed that the developed FM can reduce friction even in milder sliding environments—where the onset of mixed lubrication is delayed—by suppressing metallic contact between sliding parts more effectively than conventional FMs can [23, 24].

It should be noted that all the test oils evaluated in this study utilize a newly developed additive formulation for EV oils, which gives them excellent extreme pressure properties and material compatibility required for EV applications. This additive formulation is designed to satisfy the demands for higher gear load capacity, which is necessary due to the miniaturization and higher rotational speeds of e-axes, as well as requirements for material compatibility, such as preventing corrosion of copper components and maintaining the tensile strength of formed-in-place gaskets (FIPGs) [2, 3, 9, 28–31].

MTM Test for Friction Characteristics

For the friction tests conducted in the laboratory evaluation, a mini traction machine (MTM), as shown in Figure 4,

FIGURE 4 MTM test.

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TABLE 2 MTM test conditions.

Load, N (P ave. GPa)	70 (0.8)
Temperature, °C	60
Velocity, m/s	0.03–3.0
Slip rate, %	5

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was used to assess the friction characteristics of the test oils listed in Table 1. The test conditions are summarized in Table 2. After running a constant-speed running-in test for 1.5 h at a circumferential speed of 0.1 m/s, the main friction test was performed. To simulate sliding on gear tooth surfaces, the slip ratio was set to 5%. Previous studies have confirmed that there is a correlation between the friction characteristics observed under these conditions and the gear efficiency measured with a gear test rig [23].

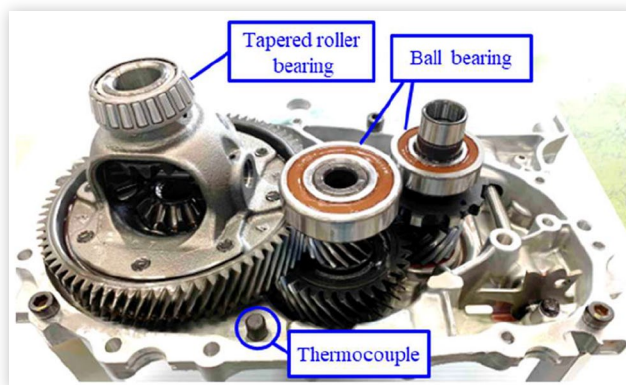
Reduction Gear Box Efficiency Test

To evaluate efficiency under practical conditions, a bench test was performed using a reduction gear box from a commercially available BEV. The specifications are listed in Table 3, and Figure 5 shows the internal appearance of the reduction gear box. An overview of the reduction gear box test bench is provided in Figure 6. The evaluation was carried out under transient conditions, using the input rotational speed and input torque profiles corresponding to the China Light-duty Vehicle Test Cycle–Passenger Cars (CLTC) mode, as driven by a commercial BEV. The time histories of the rotational speed and torque used in the

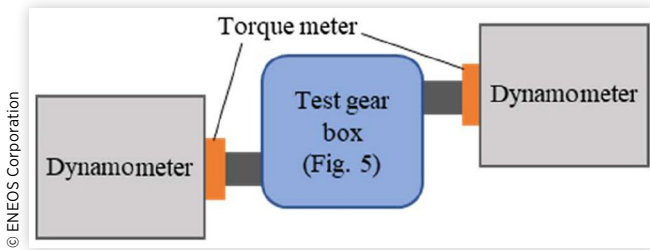
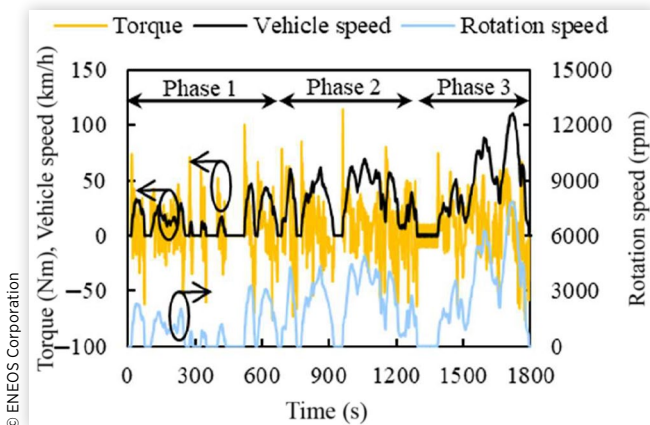
TABLE 3 Specifications of reduction gear box.

Oil capacity, L	1.5
Final gear ratio	8.2
Bearing type	Tapered roller bearing/Ball bearing
Reducer type	3 parallel axes
Lubrication method	Forced lubrication (without pump)

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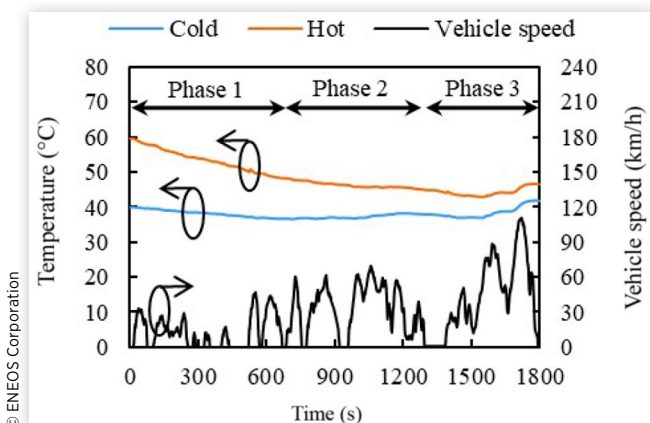
FIGURE 5 Appearance of test gear box.

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FIGURE 6 Gear box test layout.**FIGURE 7** Torque and rotation speed of transient test.

evaluation are shown in Figure 7. Under these conditions, efficiency was calculated from the rotational speed and torque measured at the input and output shafts of the tested reduction gear box.

Regarding the test oil temperature, two conditions were set: one in which the oil temperature at the start of the test was 40°C, defined as the Cold mode, and another at 60°C, defined as the Hot mode. Temperature measurements were taken by placing a thermocouple at the drain plug located at the bottom of the reduction gear box, as shown in Figure 5. Figure 8 shows the time history of oil temperature during operation for Sample B, as listed in Table 1. Since the reduction gear box is naturally cooled, the oil temperature varies with the heat generated during

FIGURE 8 Temperature of transient test.

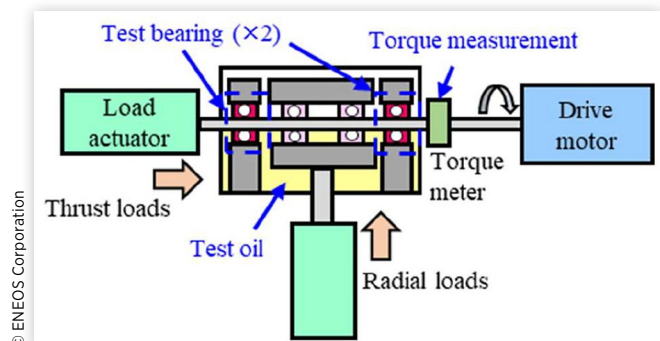
operation. As shown in Figure 8, the average oil temperature was around 38°C in the Cold mode and around 48°C in the Hot mode, with the maximum temperature difference among different oil types being about 1°C.

Oil Temperature Rise Test

Similar to the efficiency evaluation described in the previous section, this evaluation was conducted using the reduction gear box and test setup shown in Figures 5 and 6. Here, cooling performance—directly related to frictional heat generation—was assessed by measuring the oil temperature inside the unit under steady-state loaded conditions. Specifically, cooling performance was evaluated based on the extent to which the lubricant could suppress the oil temperature rise caused by frictional heat generation [4, 15]. The oil temperature at the start of the test was set to 40°C, with the input rotational speed at 1281 rpm and the input torque at 320 Nm. These conditions simulate harsh operations, such as uphill driving or durability testing, where the motor operates under severe loads, and are more demanding than the efficiency test conditions shown in Figure 7. Using this evaluation method, the effects of low viscosity, low traction, and low friction on frictional heat generation were verified for Samples A, B, D, B1, and D1 to D3 from Table 1.

Bearing Durability Test

To evaluate the durability of bearings, a component-level durability test was conducted using a dedicated test rig. An overview of the evaluation and the test conditions are shown in Figure 9 and Table 4, respectively. In this evaluation, a commercially available tapered roller bearing made of SUJ2—commonly used in reduction gear

FIGURE 9 Bearing durability test.**TABLE 4** Bearing durability test conditions.

Thrust load, kN	20
Radial load, kN	20
Rotation speed, rpm	5000
Temperature, °C	90
Bearing type	Tapered roller bearing
Lubrication method	Submerged in oil

boxes—was tested. Durability was assessed by measuring the time until pitting occurred on the tapered rollers. Pitting was determined at the moment when shaft vibration exceeded a predetermined threshold. In this test, Sample E1—which has the lowest kinematic viscosity among the oils listed in Table 1 and contains the developed FM—was evaluated. For comparison, evaluations were also conducted using a commercial EV oil with a kinematic viscosity of 12 mm²/s at 40°C and FM-free Sample E. As shown in Figure 9, the test rig is equipped with a torque meter, which was used to monitor friction throughout the test in order to evaluate the friction characteristics of the bearings with each test oil.

Gear Durability Test

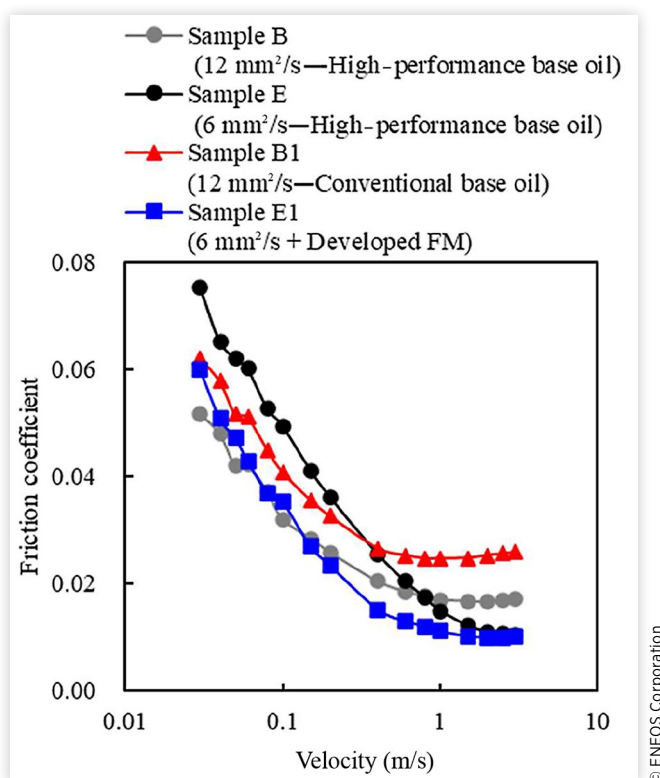
To evaluate gear durability, a durability test was conducted using a commercially available automatic transmission (AT). In this evaluation, among the various gear contacts, the differential-side reduction gear—which is subjected to the highest load—was monitored for pitting, as it is considered suitable for assessing the gear durability performance of EV oils. Pitting was inspected by visually observing the gear surface at regular intervals during operation. If the pitted area was below the predetermined threshold, the operation was continued for a set period until the threshold was exceeded, at which point the lifetime was defined. The test oil temperature was set to 90°C. In this evaluation, Sample E1 was tested, and for comparison, the aforementioned commercial EV oil was also evaluated. In addition, to examine the effect of the developed FM, both FM-free Sample D and FM-containing Sample D1 were tested.

Results and Discussion

Friction Characteristics in MTM Tests

Figure 10 shows the friction characteristics obtained with the MTM for selected test oils, highlighting the effects of low viscosity, low traction, and low friction. Sample B was evaluated in two trials. It was confirmed that the variation in friction coefficient was no greater than 0.004, with an average variation of 0.002 across the different velocity conditions. This indicates that the variation in friction coefficient is sufficiently small compared to the changes resulting from differences in formulation. Comparing the results for Sample B (with 12 mm²/s kinematic viscosity at 40°C) and Sample E (with 6 mm²/s kinematic viscosity at 40°C), which demonstrates the effect of kinematic viscosity, it can be seen that in the low-speed region below 1 m/s—where friction begins to increase—the lower-viscosity Sample E exhibits a shift in the onset of friction increase toward higher speeds. This is thought to be because, as viscosity decreases, the oil film becomes thinner and metallic contact between parts occurs at

FIGURE 10 MTM test results.

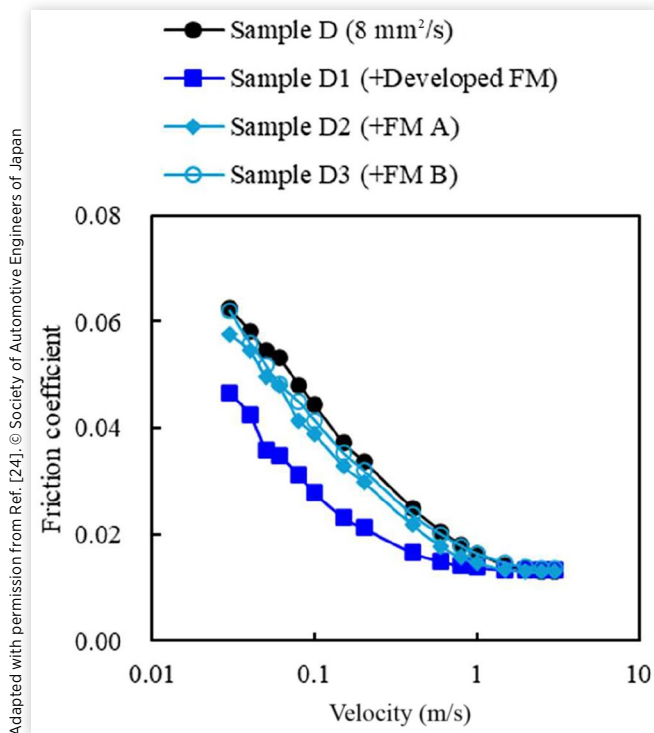


higher speeds. At a velocity of 0.03 m/s, Sample E exhibited a 46% increase in friction compared to Sample B. These trends are consistent with the findings previously confirmed by the authors [24].

Next, comparing Sample B and Sample B1, which shows the effect of high-performance base oil on traction, Sample B, with a high-performance base oil, has 34% lower friction at 2.5 m/s compared with Sample B1, which uses a conventional base oil. Comparing Sample B and Sample E, both of which use high-performance base oils, Sample E shows even lower friction at 2.5 m/s. This is likely because Sample E has a higher ratio of lower-viscosity base oils with a lower traction coefficient.

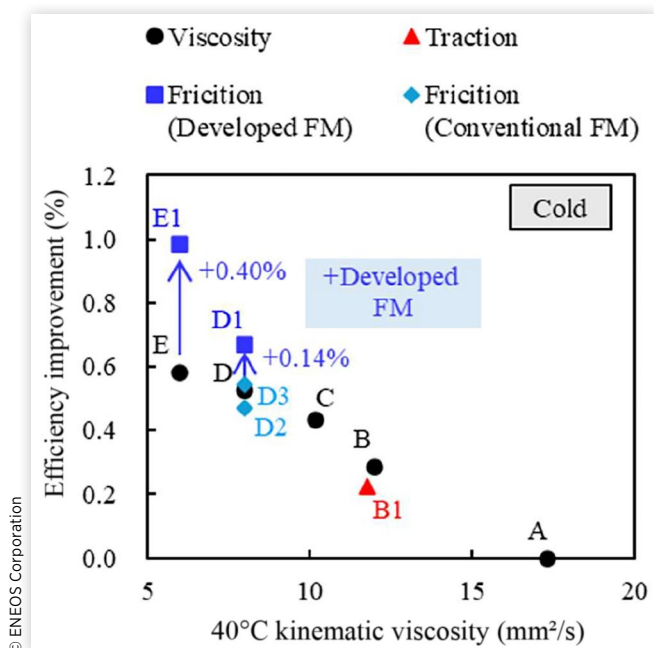
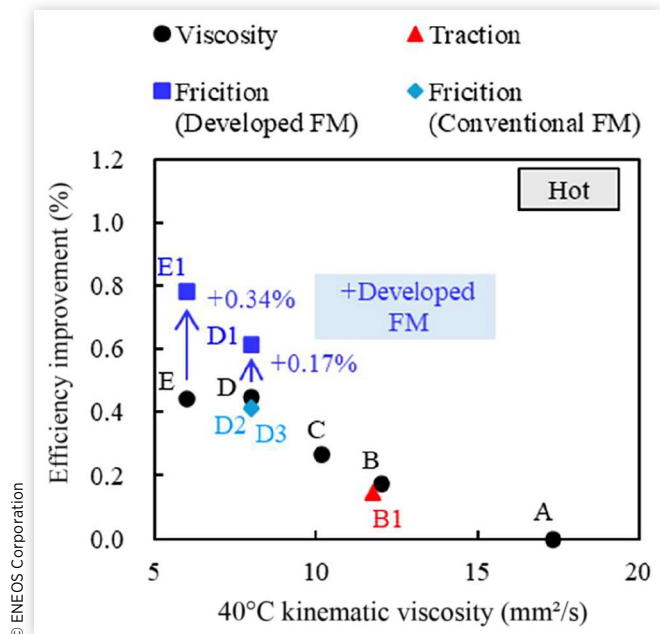
Next, a comparison of Sample E and Sample E1 reveals that Sample E1—with the developed FM—suppressed the increase in friction associated with the lower viscosity in Sample E and exhibited a friction reduction effect. At a velocity of 0.03 m/s, the friction of Sample E1 was reduced by 20% compared to Sample E.

Figure 11 shows the results for Sample D and Samples D1 to D3, demonstrating the effects of various FMs previously reported [24]. In this figure, Sample D1 with the developed FM showed a friction reduction effect similar to that of Sample E1. On the other hand, Sample D2 and Sample D3, which were blended with conventional FMs, exhibited friction characteristics similar to Sample D, and no substantial friction reduction was observed. Under the conditions tested—which simulate the sliding at gear contact points—it is considered possible that the lubrication condition was not severe enough for conventional FMs to exhibit friction reduction effects.

FIGURE 11 MTM test results (FMs).

Reduction Gear Box Efficiency

The relationship between kinematic viscosity and the efficiency improvement of each test oil relative to Sample A is shown in Figure 12 for the Cold mode and in Figure 13 for the Hot mode. In both figures, the 40°C kinematic viscosity of each test oil is plotted on the horizontal axis, with the corresponding test oil name indicated by an

FIGURE 12 Efficiency test results (Cold mode).**FIGURE 13** Efficiency test results (Hot mode).

alphabetical character near each plot point. Black points indicate an evaluation of low viscosity, red points indicate low traction, and blue points indicate low friction. During the series of evaluations, a commercial EV oil with a kinematic viscosity of 12 mm²/s at 40°C was tested multiple times, and it was confirmed that the variation in efficiency was no greater than 0.04%.

Looking at the results for Sample A (with 17 mm²/s kinematic viscosity at 40°C) through Sample E (with 6 mm²/s kinematic viscosity at 40°C), which were used to examine the effect of kinematic viscosity, it can be seen in both figures that efficiency improvement correlates with lowered viscosity. However, comparing Cold mode (Figure 12) with Hot mode (Figure 13), it can be seen that the efficiency improvement effect due to lower viscosity becomes less pronounced in the Hot mode. This is likely because the higher average oil temperature in the Hot mode causes the viscosity of each oil to be lower and the viscosity differences among the oils to become smaller. Furthermore, the proportion of more severe lubrication conditions with thinner oil films increases in the Hot mode, so the effect of increased metal contact due to lower viscosity becomes more significant, possibly resulting in a weaker efficiency improvement effect. In the Hot mode, Sample E with lower viscosity actually showed slightly lower efficiency compared with Sample D, confirming, as was seen in previous studies, that excessive viscosity reduction can lead to reduced efficiency [10–12, 23].

Regarding the effect of lowering traction, the MTM test showed that Sample B achieved a 34% reduction compared with Sample B1, whereas in the reduction gear box, an efficiency improvement of +0.06% was observed in the Cold mode.

As for the effect of lowered friction, Sample D1 (with 8 mm²/s kinematic viscosity at 40°C with the developed FM) showed an efficiency increase of +0.14% in the Cold

mode and +0.17% in the Hot mode compared with Sample D (without FM). For Sample E1 (6 mm²/s at 40°C with the developed FM), the improvement was +0.40% in the Cold mode and +0.34% in the Hot mode compared with Sample E (without FM). These results indicate that the efficiency improvement from the developed FM becomes larger as the viscosity of the test oil decreases. This is considered to be due to the suppression of metallic contact and the associated reduction in friction losses. Since the friction loss without FM increases as the viscosity decreases, the improvement effect becomes greater with lower viscosity, resulting in a more pronounced efficiency benefit. Thus, it can be concluded that the developed FM can suppress the loss increase caused by lowering viscosity and enable further efficiency improvement. Compared with Sample A, Sample E1 showed a maximum efficiency improvement of about +1.0% in the Cold mode.

Additionally, for Sample D2 and Sample D3 (with conventional FMs) in the reduction gear box, the maximum efficiency improvement in the Cold mode was only +0.01%, demonstrating a negligible effect. In light of the friction characteristics measured by the MTM in Figures 10 and 11, this evaluation suggests that the developed FM exhibited a friction reduction effect, while the conventional FMs did not.

Figure 14 shows the efficiency improvement of Sample E1, which had the highest efficiency improvement among the test oils (with a kinematic viscosity of 6 mm²/s at 40°C) relative to a commercial EV oil with a kinematic viscosity of 12 mm²/s at 40°C. As shown in the figure, Sample E1, which was formulated with the developed FM and reduced viscosity, achieved efficiency improvements of +0.88% in the Cold mode and +0.77% in the Hot mode.

As described above, the effects of lowering viscosity, lowering traction, and lowering friction on efficiency improvement under transient conditions were separated and analyzed, allowing confirmation of effective methods for energy saving.

Regarding the efficiency improvement with EV oils, it was observed that, for test oils without FM, the

improvement from lower viscosity became less pronounced under certain conditions. On the other hand, the application of low-friction technology was found to overcome the disadvantages of lowering the viscosity, making further energy savings possible. Furthermore, it is expected that low-friction technology could enable even greater energy savings by lowering the viscosity below 6 mm²/s at 40°C, although it would then be necessary to address other properties such as flash point in this viscosity range.

In this evaluation, the effect of elastohydrodynamic lubrication was minor; however, it is expected that its effect could vary depending on unit parts and sliding environments. In actual development of energy-saving EV oils, it is considered essential to carefully assess the effect of each lubrication on efficiency for the target unit and to apply the appropriate technology to the EV oil accordingly.

Oil Temperature Rise Characteristics

Figure 15 shows the oil temperature profiles during the evaluation for selected test oils, highlighting the effects of low viscosity, low traction, and low friction.

Looking at the temperature profiles shown in Figure 15, it can be seen that there are differences in the rate of temperature increase among the four test oils. As mentioned earlier, higher friction in the test oil is expected to lead to greater heat generation and, consequently, poorer cooling performance.

Regarding the effect of lowering viscosity, Sample B and Sample D differ by 4 mm²/s in their kinematic viscosity

FIGURE 14 Efficiency test results (Sample E1).

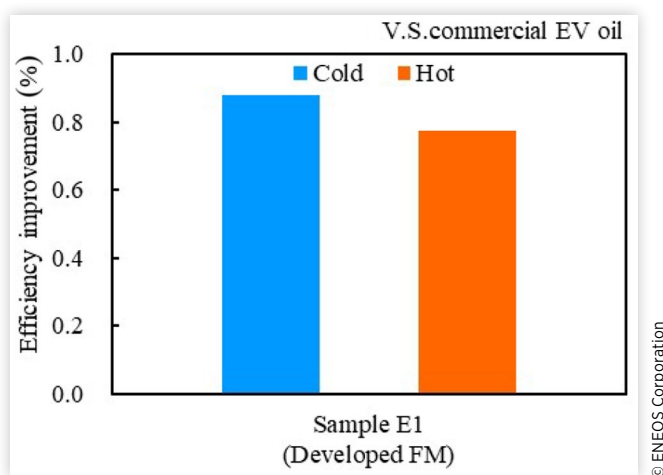
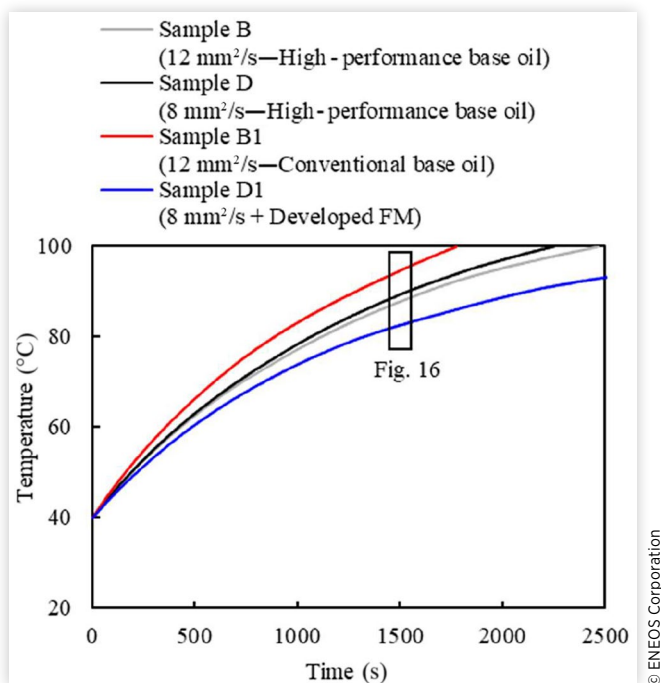


FIGURE 15 Temperature profile.



at 40°C, with Sample D having the lower viscosity. In the comparison, Sample D exhibited a slightly faster rate of temperature rise, indicating inferior suppression of frictional heat generation. The low-traction Sample B, which uses a high-performance base oil, had a slower rate of temperature rise relative to that of Sample B1 with a conventional base oil, confirming its superior suppression of frictional heat generation. Sample D1, to which the developed FM was added, showed a slower temperature rise compared with the FM-free Sample D, indicating better suppression of frictional heat generation. Since Sample D1 uses a low-traction base oil and also contains the developed FM, it exhibited the best suppression of frictional heat generation among the four test oils.

Figure 16 summarizes how low viscosity, low traction, and low friction contribute to changes in oil temperature, based on the oil temperature at 1500 s after the test started (indicated by the black box in Figure 15). The alphabet letters in the figure indicate the sample names, and the values show the differences in oil temperature at 1500 s for each candidate oil. For example, the result on the far left shows the temperature difference between Sample B and Sample A, with a positive value indicating a lower temperature at 1500 s and thus superior suppression of frictional heat generation. In this way, the impact of low viscosity, low traction, and low friction on oil temperature was clarified by analyzing the temperature differences for each candidate oil.

Considering the effect of kinematic viscosity, the results for Sample A, B, and D indicate that lowering the viscosity from 17 mm²/s to 12 mm²/s at 40°C leads to a decrease in temperature, while a further reduction to 8 mm²/s results in an increase in temperature. This is thought to be because, similar to the efficiency tests described earlier, lowering the viscosity to below 12 mm²/s at 40°C increases the proportion of severe lubrication conditions with thinner oil films, which in turn leads to increased metal-to-metal contact and thus greater heat generation. However, the effect of the viscosity change is only about 1°C in both cases, which is relatively small

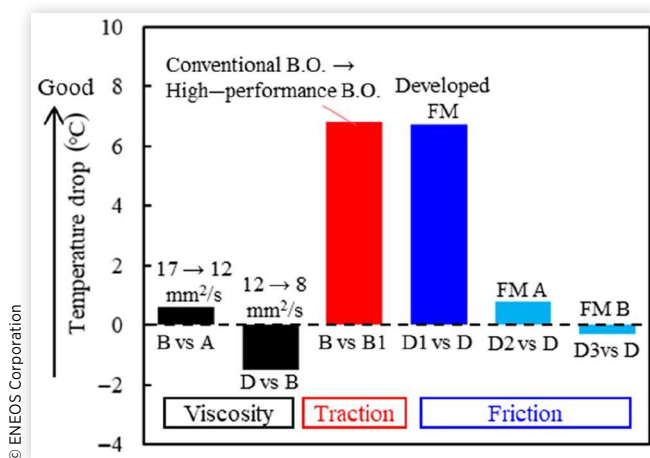
compared with the effects of traction and friction reduction with the developed FM.

Looking at the effect of traction, a comparison of Sample B and B1 shows that the low-traction Sample B, formulated with a high-performance base oil, demonstrated an approximately 7°C decrease in temperature compared with Sample B1. This temperature reduction effect is greater than that achieved by lowering viscosity. In terms of the efficiency improvements shown in Figures 12 and 13, viscosity reduction appeared to offer a greater improvement than traction reduction. The difference in the effects of low viscosity and low traction between the two tests is assumed to be due to the much higher torque applied in the present test compared with the efficiency test; this resulted in more severe lubrication conditions, with a greater influence from elastohydrodynamic lubrication.

With respect to friction reduction, comparison of Sample D and D1–D3 shows that Sample D1, which includes the developed FM, achieved an approximately 7°C temperature reduction compared with Sample D. In contrast, Sample D2 and D3, with conventional FMs, showed changes of less than 1°C. On the basis of the friction characteristics obtained in the MTM test shown in Figure 11, it can be concluded that, even under harsher test conditions, the conventional FM could not provide friction reduction, whereas the developed FM demonstrated a friction reduction, thereby contributing to suppression of heat generation and improved cooling performance.

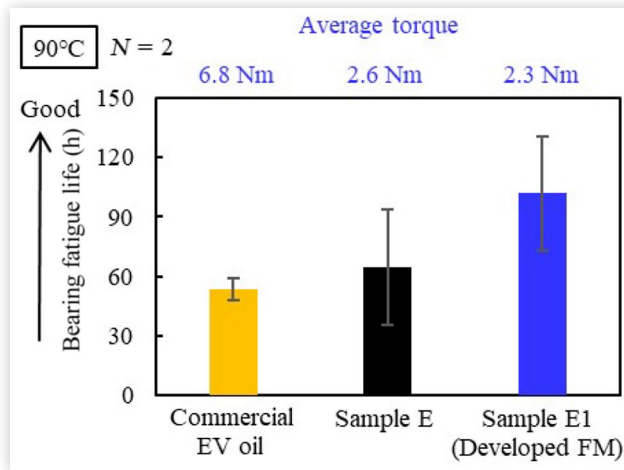
It should be noted that the cooling performance evaluation in this study focused exclusively on the reduction gear box, specifically investigating the suppression of frictional heat generation. As shown in the previous section, excessive viscosity reduction in FM-free test oils resulted in lower efficiency, but it was demonstrated that combining the low-friction technology of the developed FM allows for further viscosity reduction, which is also effective in improving cooling performance by enhancing heat removal. In addition to the evaluation of heat generation performed here, to evaluate cooling performance while considering heat removal, it is desirable to conduct tests with oil cooling systems including the motor; such an evaluation will be a subject for future research.

FIGURE 16 Temperature drop (effect of viscosity, traction, friction).



Bearing Durability Performance

Figure 17 shows the bearing failure time and average torque during the test as obtained from the evaluation. As shown in the figure, Sample E1, which demonstrated the highest energy efficiency, exhibited approximately twice the failure time compared with the commercial EV oil, with a kinematic viscosity of 12 mm²/s at 40°C, thereby confirming excellent bearing durability. For comparison, Sample E, which does not contain the FM, showed a lifespan equivalent to or only slightly better than the commercial EV oil. Comparing the average torque during the test, Sample E1 achieved about a 10% reduction compared with Sample E and about a 70% reduction relative to the commercial oil.

FIGURE 17 Bearing durability test result.

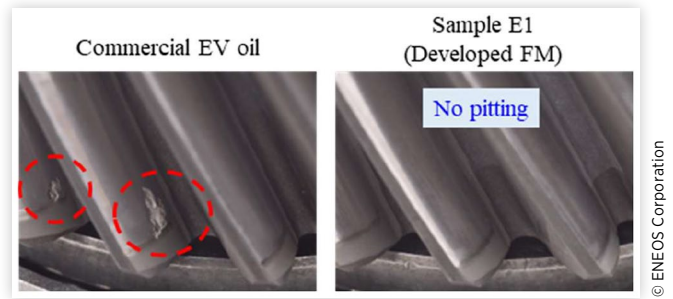
From the results for Sample E and Sample E1, it can be concluded that the favorable durability performance of Sample E1 is due to the effect of the developed FM. The approximately 10% reduction in average torque compared with Sample E is considered an effect of the suppression of metallic contact at the bearing sliding surfaces by the FM, as suggested by the friction reduction effects observed in the MTM test in Figure 10. This suppression of metallic contact likely helped to improve durability by reducing metal fatigue on the component surfaces. On the other hand, in comparison with the commercial EV oil, Sample E recorded a lower average torque, but its lifespan was equivalent to or only slightly better, indicating that there was no clear correlation between average torque and durability performance. It has been previously confirmed that the formation of protective films containing phosphorus, calcium, and other elements from additives on sliding surfaces can affect fatigue life [5, 18]. In the performance comparison with the commercial EV oil, it is supposed that differences in additive formulations of the test oils resulted in the formation of different films on the sliding surfaces, which led to the observed lack of correlation between average torque and durability performance; further investigation is necessary to clarify the mechanism behind these findings.

Gear Durability Performance

Table 5 presents the results for each test oil based on the durability time of the commercial EV oil as a reference. For all samples except Sample E1, the durability data had

TABLE 5 Mission durability test results.

Sample	Commercial EV oil	Sample D	Sample D1	Sample E1
40°C KV, mm ² /s	12	8	8	6
Developed FM	—	—	○	○
Durability time (compared with commercial EV oil)	1×	1×	>2×	>2×

FIGURE 18 Gear surface appearance after durability test.

been previously obtained [24]. As shown in the table, Sample E1, which demonstrated the highest energy efficiency, exhibited no gear pitting even after twice the durability time of the commercial EV oil had elapsed, indicating excellent durability performance. Figure 18 shows photographs of the gear surfaces of the commercial EV oil and Sample E1 after the completion of this evaluation.

Additionally, the durability of Sample D without FM was equivalent to that of the commercial EV oil, while Sample D1 with the developed FM showed results similar to Sample E1. Since Sample D without FM exhibited durability equivalent to the commercial EV oil, it was confirmed that the favorable durability of Sample D1 and Sample E1 was largely due to the effect of the developed FM. Similar to the bearing durability results described in the previous section, this is assumed to be an effect of the developed FM suppressing metallic contact at the gear sliding surfaces, thereby mitigating metal fatigue on the part surfaces.

Summary

Through this study, an EV oil with a kinematic viscosity at 40°C of 6 mm²/s—significantly lower than that of commercial EV oils—was successfully developed, demonstrating superior energy efficiency and cooling performance. The following key findings were obtained:

1. Through efficiency evaluations of the reduction gear box simulating the CLTC mode, the effects of low viscosity, low traction, and low friction in EV oils were verified. As a result, it was found that combining low viscosity with the developed FM for friction reduction effectively prevents efficiency degradation caused by excessive viscosity reduction and is highly effective for energy saving. In particular, it was found that lowering the kinematic viscosity to 6 mm²/s at 40°C and applying the developed FM improved efficiency by approximately +0.8 to +0.9% compared to a 12 mm²/s (40°C) commercial EV oil.
2. Through oil temperature evaluations based on frictional heat generation using a reduction gear box, the effects of low viscosity, low traction, and low friction in EV oils were investigated. As a

result, under conditions of an input speed of 1281 rpm and input torque of 320 Nm, it was confirmed that the low traction achieved with high-performance base oil and the low friction achieved with the developed FM are effective in reducing parasitic heat losses.

3. To assess the durability, which is a concern with lowered viscosity, both bearing and gear durability tests were conducted. As a result, it was found that, by applying the developed FM, the test oil with a kinematic viscosity of 6 mm²/s at 40°C exhibited twice the bearing durability and more than twice the gear durability compared with the use of commercial EV oil. The developed FM was thus found to be effective in improving the durability of various parts.

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