

Low-viscosity Gear Oil Technology to Improve Wear at Tapered Roller Bearings in Differential Gear Unit

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ABSTRACT

Torque loss reduction at differential gear unit is important to improve the fuel economy of automobiles. One effective way is to decrease the viscosity of lubricants as it results in less churning loss. However, this option creates a higher potential for thin oil films, which could damage the mechanical parts. At tapered roller bearings, in particular, wear at the large end face of rollers and its counterpart, known as bearing bottom wear is one of major failure modes. To understand the wear mechanism, wear at the rolling contact surface of rollers and its counterpart, known as bearing side wear, was also observed to confirm the wear impact on the tapered roller bearings. Because gear oils are also required to avoid seizure under extreme pressure, the combination of a phosphorus anti-wear agent and a sulfurous extreme pressure agent are formulated. Because the latter could cause an antagonistic impact on the former, we focused on control of active sulfur content as well as the treat ratios to reduce wear at the tapered roller bearing while maintaining anti-seizure. Additive screening bench tests were performed considering operational conditions in actual gear unit-stand tests on the basis of the above-mentioned concept and the best formulation was identified as a breakthrough for low-viscosity gear oil. This low-viscosity gear oil technology was validated in the unit-stand tests. The sample oil based on the technology demonstrated equivalent performance for anti-wear while maintaining good anti-seizure, to the high-viscosity gear oil.

CITATION: Mori, T., Suemitsu, M., Umamori, N., Sato, T. et al., "Low-viscosity Gear Oil Technology to Improve Wear at Tapered Roller Bearings in Differential Gear Unit," *SAE Int. J. Fuels Lubr.* 9(3):2016, doi:10.4271/2016-01-2204.

INTRODUCTION

Wear at tapered roller bearings in differential gear units should be restrained because it causes vibration after the unfavorable clearance increase in the axial direction exceeds certain threshold, which could severely damage other parts in the drivetrain (Fig.1). The clearance increase is measurable by the assembled bearing width (Fig.2).

Numerous studies focusing on friction, lubrication, wear, and other related subjects at the large end face of rollers and bearing bottom wear [1, 2, 3, 4, 5, 6, 7, 8] exist. Much less has been written on wear at the rolling contact surface of rollers and bearing side wear. In consequence of the investigation on both wear, the authors discovered that bearing side wear is indeed smaller than bearing bottom wear in terms of wear depth, but the smaller wear depth highly impacts the assembled bearing width reduction. This impact is caused by the contact angle between axial direction and rollers or raceways. This will be discussed in the "Wear area investigation" section.

To formulate differential gear oils, phosphorus anti-wear (AW) and sulfurous extreme pressure (EP) agents are widely employed to avoid wear, seizure, and other damages at bearings or gears [9-10].

Although both additives could mutually cause an antagonistic impact, in this study, by controlling the active sulfur content in the sulfurous EP agent as well as the treat ratios of both additives, the trade-off relation between anti-wear and anti-seizure was overcome and then the optimum treat rate of the EP and AW agents was studied.

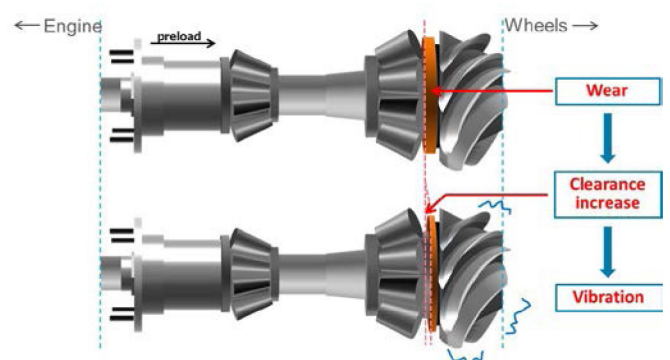


Fig 1. Impact of wear on assembled bearing width reduction and vibration

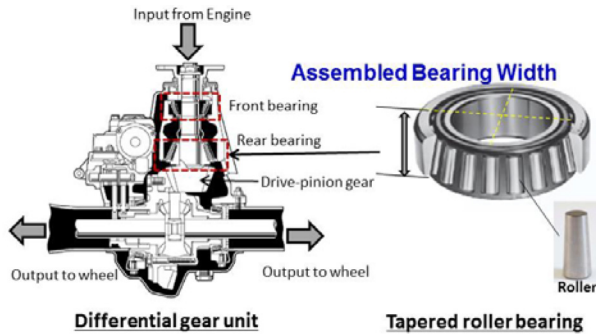


Fig 2. Assembled bearing width view

Additive screening bench tests were performed considering operational conditions in actual gear unit-stand tests. As a validation test, the actual differential gear unit-stand tests were performed and the formulation demonstrated equivalent performance in anti-wear and anti-seizure to the high-viscosity gear oil.

TEST METHODS

Test Sample Oils

To identify the impact of lowering viscosity, two modes of differential gear unit-stand tests were conducted with four oil samples having different viscosities and additive formulations, as summarized in Table 1. DGO1 is a commercial and field-proven product for Toyota's vehicles for over 30 years. DGO2 to DGO4 are low-viscosity experimental samples. DGO2 and DGO3 were initially set to confirm the impact of lowering viscosity from DGO1 and the impact of the sulfurous EP agent.

Two types of sulfurous EP agents S-1 and S-2 are employed for the experimental samples. Both the agents are sulfurized olefins, with S-1 having a higher active sulfur content than S-2. Active sulfur content is the quantity of sulfur available to react with the metallic surface and is determined by ASTM D1662.

Table 1. Test oil samples for gear unit-stand tests

	DGO1	DGO2	DGO3	DGO4
KV40, mm ² /s	182	73		
KV100, mm ² /s	17	11		
Sulfurized olefin	-	S-1	S-2	
Active sulfur content	-	High	Low	
Sulfur content, mass%	2.8	2.1	4.4	3.3
Phosphorus content, mass%	0.12	0.14	0.12	0.14

A two-factor experiment using sample oils based on DGO3 but having different treat ratio combinations of EP agent and AW agent was conducted by bench test and DGO4 providing better anti-wear performance was formulated as indicated in the "Formulation study" section.

Differential Gear Unit-Stand Tests

A unit-stand test called the "patterned durability test" is designed to evaluate the overall performance of gear oils in terms of hardware protection to the extent of damage after the test. It simulates actual unit operations in the field with sequential driving patterns including constant high-speed and repetitive acceleration and deceleration modes to include a wide range of lubricating conditions. Oil temperature at the beginning of each driving pattern was set at 120 °C or higher depending on the driving pattern. The primary evaluation purpose of the test is to confirm the amount of change in the assembled bearing width of the tapered roller bearing. Another unit-stand test is the "differential gear seizure test," which is used to evaluate the anti-seizure performance using the torque value at the ring gear when seizure occurs. In this test, the differential rotation speed is fixed and the torque at the ring gear is increased in a stepwise manner until seizure occurs.

Bench Tests

To work on the optimized treat rate of sulfurous EP and phosphorus AW agents in terms of anti-wear performance, bench tests were conducted based on ASTM D 4172, with the test conditions reflected from the actual bearing operation.

RESULTS AND DISCUSSION

Differential Gear Unit-Stand Tests

The results of differential gear unit-stand tests were shown in Fig.3. The low-viscosity DGO3 showed better anti-seizure, whereas the low-viscosity DGO2 performed poorer than DGO1 in the differential gear seizure tests.

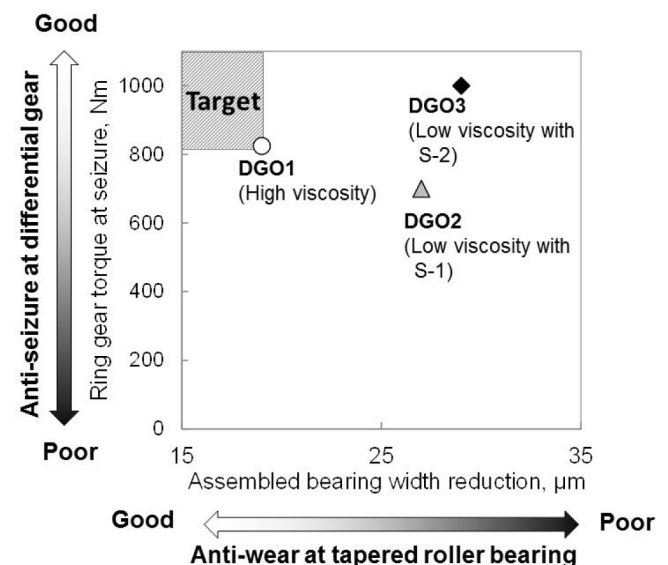


Fig 3. Results of patterned durability and differential gear seizure tests

DGO3 needs to be improved in anti-wear at the tapered roller bearing, whereas DGO2 needs improvement in both anti-wear at the tapered roller bearing and anti-seizure at the differential gear. Therefore, a formulation study was conducted based on DGO3 having sulfurous EP agent S-2, which has a lower active sulfur content.

Wear Area Investigation

The presumable worn area for a tapered roller bearing is illustrated in Fig.4. It is divided into two large groups. One is the bearing bottom wear, which consists of wear at the large end face of the rollers and the cone back face rib. Another one is the bearing side wear, which consists of wear at the rolling contact surface of the rollers and the corresponding raceways.

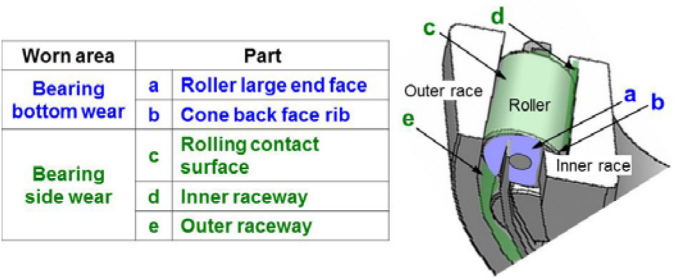


Fig 4. Worn area of bearing

The surface profile was measured at five parts. The cross-section diagram is indicated in Fig.5 (I). The sum of the wear depth value is shown in Fig.6. It consists of 10-13 μm as the bearing bottom wear and 2-4 μm as the bearing side wear (Fig.6).

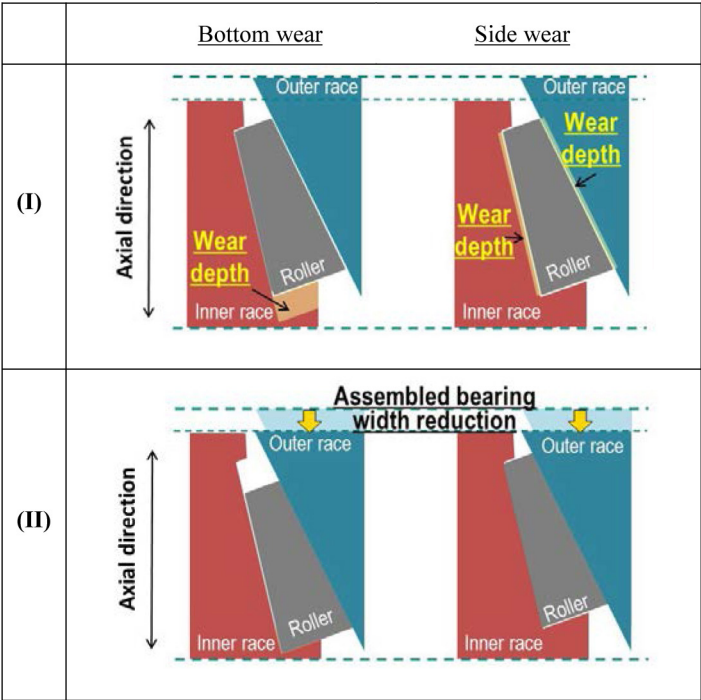


Fig 5. Impact of wear depth on assembled bearing width reduction

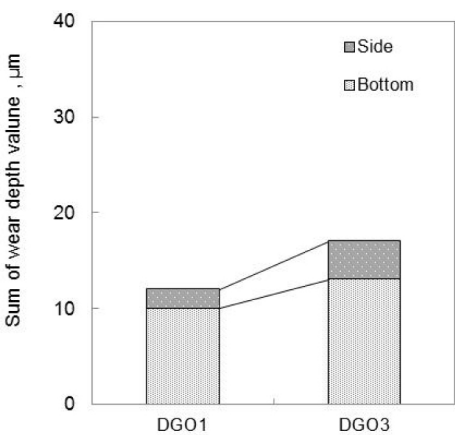


Fig 6. Sum of wear depth value (rear bearing)

The estimated breakdown of the assembled bearing width reduction is calculated as 11-14 μm and 9-15 μm for the bearing bottom wear and bearing side wear by equation (1) and (2), respectively. The equations are determined by the configuration of bearings; the coefficient is defined by contact angle between each surface and axial direction. Even a small impact of the bearing side wear on the assembled bearing width reduction was observed to be almost equivalent to that of the bearing bottom wear in Fig.7, whose mechanism is illustrated in Fig.5 (II).

Estimated assembled bearing width reduction by bottom wear

$$= 1.1 \times [\text{wear depth at a and b}]$$

(1)

Estimated assembled bearing width reduction by side wear

$$= 2.6 \times [\text{wear depth at c and d}]$$
$$+ 3.7 \times [\text{wear depth at c and e}]$$

(2)

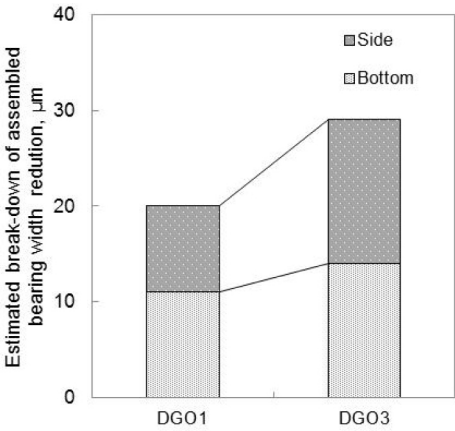


Fig 7. Estimated breakdown of assembled bearing width reduction (rear bearing)

The improvement in the bearing side from DGO3 was focused to achieve the same level of the assembled bearing width reduction as DGO1 because of the larger difference in bearing side wear than the bottom wear between DGO1 and DGO3.

Formulation Study

Chemical elements on the rubbing surface of the bearing components after the patterned durability test were analyzed using SEM-EDX. The analyses indicated that higher phosphorus content on the surface had a lower value of wear depth (Fig.8).

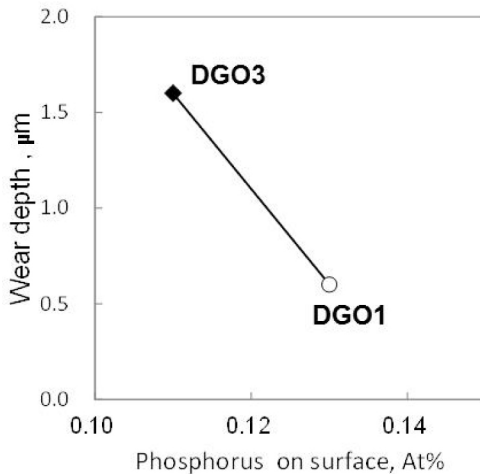


Fig 8. Correlation between phosphorus on surface and wear depth after patterned durability test

Some other examinations such as surface observation, analyzing iron content in test oil sample after the patterned durability test, and ferrography were additionally performed to investigate the wear characteristics. No significant difference in the feature of wear was observed between DGO1 and DGO3. The surface appeared to have normal wear, different from abrasive or corrosive wear, indicating that the anti-wear phosphorous film formed sufficiently on the surface and was the key to improve the wear, as shown in Fig.8.

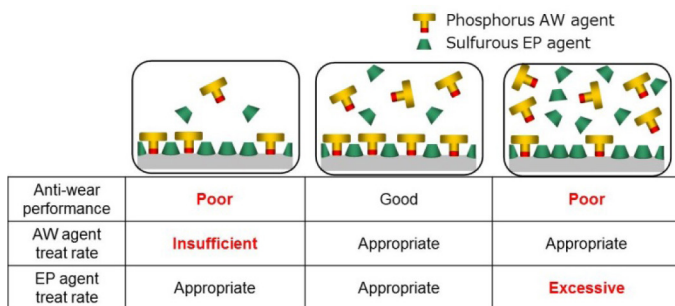


Fig 9. Conceptual diagram of additive behavior on rubbing surface

One possible approach to promote the action of the phosphorus AW agent on the rubbing surfaces is to formulate more AW agents. In Fig.9, competitive surface adsorption occurs between the AW and

sulfurous EP agents, and the insufficiently treated AW agent could cause less phosphorous film formation interrupted by EP agents on the surface (Fig.9) because of the smaller amount of AW agents.

Another approach is to have a down-treated sulfurous EP agent because the excessively treated sulfur of DGO3 could prevent the AW agents from forming a phosphorous film, as illustrated in Fig.9. This is possible because DGO3 exhibited good anti-seizure performance vs. DGO1, as shown in Fig.3. A lesser treatment of the EP agent could still achieve good anti-seizure performance. Thus, a formulation matrix study on the anti-wear performance was conducted using bench test as a function of the sulfurous and phosphorous levels treated in test oils.

The screening bench test identified the optimized sulfurous and phosphorus treat rate to set up DGO4 in Fig.10. This test result correlates well with the expected additive interaction mechanisms in Fig.9. The excessive treat rate of the AW agent was also shown to have an increased wear in Fig.10, probably owing to a corrosive wear. Thus, the AW agent needs to be highly treated to ensure anti-wear performance at lower viscosity oil, whereas excessive treatment of the AW agent would worsen wear protection. Therefore, the DGO4 formulation was selected at the bench test to confirm the actual anti-wear performance in bearing side wear particularly, in the actual unit-stand tests.

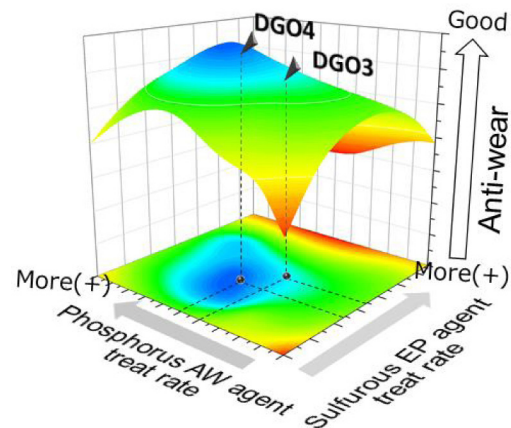


Fig 10. Optimization of additive treat rate

Validation by Unit-Stand Tests

The unit-stand tests were conducted with DGO4 to verify the improvements in anti-wear and anti-seizure. As a final verification, the assembled bearing width reduction for the front and rear bearings was measured in the patterned durability test. DGO4 demonstrated an equivalent performance in anti-wear to DGO1, which has higher viscosity, while maintaining good anti-seizure performance, as shown in Fig.11.