

Effects of hydraulic oil and lubricant additives on dynamic friction properties under various reciprocating sliding conditions

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Abstract: The friction characteristics of a shock absorber are very complex because the reciprocating motion is not always identical. In this study, a device was developed and used to analyze the dynamic friction characteristics under various reciprocating sliding conditions to determine the sliding materials and hydraulic oils that improve the shock absorber performance. This study describes the influence of hydraulic oil additive on the fine reciprocating friction characteristics of steel and copper alloy. Hydraulic oils were prepared by blending a paraffinic mineral oil with zinc dithiophosphate (ZnDTP) and polyhydric alcohol ester as additives. The results show that the dynamic frictional characteristics vary mainly depending on the additive concentration. A specific additive formulation induces a unique amplitude-dependent friction behavior. In addition, the influence of different additives on the lubrication mechanism is investigated based on the instrumental analysis of the friction surface.

Keywords: shock absorber; dynamic friction; reciprocating friction; additive; zinc dithiophosphate (ZnDTP)

1 Introduction

Nowadays, the cars travel mostly on relatively smooth roads because the road surface has progressively become less irregular due to improved road maintenance. Under such road conditions, a shock absorber, which is a key component in stabilizing car behavior, operates at a fine amplitude of several hundred micrometers to a few millimeters, such that it does not generate sufficient hydraulic pressure for the damping force. In this case, friction, which is generated by the sliding parts lubricated with hydraulic oil under reciprocating motion in the shock absorber, has larger influence on vehicle motion [1]. In addition, the friction characteristics of the shock absorber are very complex because the reciprocating motion is not identical at all times.

During reciprocation in a shock absorber, a spike-

like friction (static friction) is observed near zero velocity [2], as shown in Fig. 1. In shock absorbers, the hydraulic damping force is small near zero velocity and in the vicinity of the minute velocity range, and the frictional force generated under the influence of additives has a greater effect on ride comfort and steering stability.

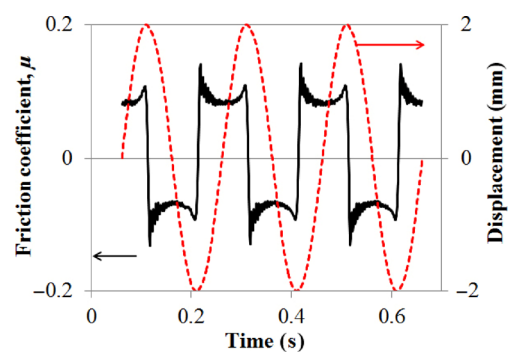


Fig. 1 Example of dynamic friction behavior.

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Shock absorbers consist of three sliding elements: cylinder/piston, piston rod/rod guide, and oil seal/piston rod [3]. The sliding elements are lubricated with hydraulic oil. The friction characteristic of shock absorber is influenced by surface roughness, material combination of the sliding elements, and hydraulic oil. Specifically, hydraulic oil has a substantial effect on the shock absorber performance [1]. Figure 3 shows the measurement of friction characteristics using the hydraulic fluid of a shock absorber that is actually used. The results show the existence of various friction characteristics [4].

Typically, hydraulic oil consists of base oil, and some additives such as friction modifier (FM), anti-oxidant, and viscosity index improver. The FMs change the friction characteristics by forming an adsorption film or a chemical reaction film on the surface, which are often known as tribo-film [5]. Esters, amides, and amines are typical FMs that adsorb on a solid surface [6]. Zinc dithiophosphate (ZnDTP), which is the most common multi-functional additive, also largely affects friction by forming a chemical reaction film [7].

Non-linear friction characteristic that is generated during reciprocation has been extensively studied in the field of robotics and servomotors, which are used for positioning control [8, 9]. Additionally, a number of studies regarding the friction between lubricants and their additives have been reported, which reveal the lubrication mechanism of friction films, including speed-dependent friction properties [10, 11]. However, these studies mostly discuss friction properties in terms of average friction. Thus far, no studies have been reported on the dynamic friction properties of friction films focusing on boundary lubrication near zero speed, under boundary lubrication conditions of lubricants with additives in reciprocating motion.

In this study, via a newly developed dynamic friction behavior measurement system, the additives used in general lubricating oils and hydraulic oil of shock absorbers are evaluated to investigate the effects of various additives on the lubrication mechanism through instrumental analysis of the friction surface. Two additives are selected, ZnDTP, which is a multifunctional additive that forms a chemical reaction film, and polyhydric alcohol ester, which is an additive of chemical adsorption film.

2 Measurement method for dynamic friction characteristics

2.1 Dynamic friction measurement system

In the reciprocating motion, there are repeated transitions from static friction to kinetic friction when the direction of motion reverses. It is common to consider that the displacement has a sine-function dependence on time to reproduce this behavior using a friction test device. The behavior of an actual shock absorber is close to a sine waveform, but the frequency and amplitude are not constant [12]. Therefore, for the reciprocating motion friction test device used in this study, the dynamic friction characteristics are measured and evaluated by representing the time evolution in displacement with sine wave functions by varying the amplitude and frequency. Figure 2 shows the schematic of the friction test device of reciprocating pin-on-disk type that is developed in this study. In this device, an electromagnetic oscillator causes a disk sample fixed on a slide bearing to perform reciprocating motion, and sliding occurs as a pin sample is pressed against the disc. As we focus on the friction characteristics under boundary lubricating condition, the point contact geometry is applied. The friction force is measured using a strain gauge attached to the fixed axle of the pin sample. A temperature controller is used to maintain a constant friction plane temperature.

2.2 Measurement method

The friction measurement conditions are set as shown

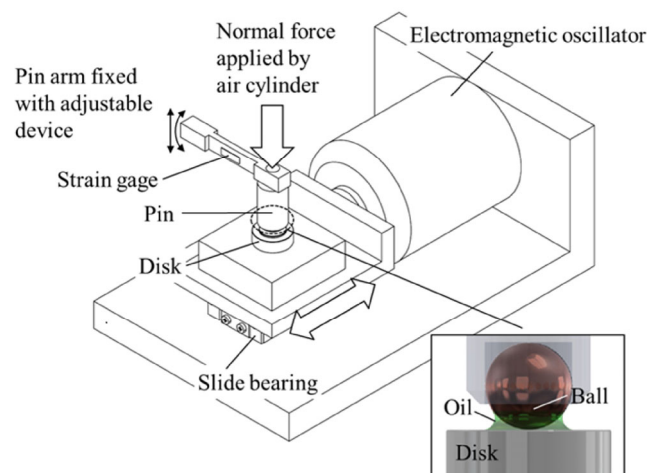


Fig. 2 Schematic of reciprocating tribo-tester.

in Table 1. The friction speed varied from very slow speeds to approximately 60 mm/s, with amplitudes of ± 0.1 to ± 2.0 mm and 5 Hz frequency.

For a shock absorber for a general passenger car, the speed at which the hydraulic damping force is similar to the frictional force is approximately 60 mm/s. This speed was set as the top speed. The set load was assumed to be approximately 20 times as stressed as the calculated projected surface pressure, assuming that the bearing is at one end.

Before each measurement, running-in was performed 300 times (60 s), at amplitude of ± 2.5 mm, to reach a steady state. The friction can change during the running-in period due to the contact area enlargement by the wear of pin and tribo-film formation with additive effect.

Additionally, in order to eliminate the influence of the previous test and stabilize the lubrication condition of each test condition, the sample is raised once before the arriving at a state in which the hydraulic fluid exists within the sliding interface, and friction force measurements were started after the pre-friction of 150 repetitions (30 s).

2.3 Evaluation sample

Shock absorbers consist of three sliding parts. In this study, we focus on the sliding part between the cylinder and piston band as one combination of sliding elements. The cylinder is made of steel and the piston band has copper dispersed in the polytetrafluoroethylene (PTFE)-based piston band material. To simulate this combination of sliding parts by the pin-on-disk

Table 1 Sliding test conditions.

Normal force	20 N
Temperature	30 °C
Amplitude	$\pm 0.1, 0.2, 0.5, 1.0, 2.0$ mm
Frequency	5 Hz
Oscillating mode	Sine wave
Maximum velocity	3.14–62.8 mm/s
Ball sample	Copper (>99.9% Cu) 1/2 inch diameter
Disk sample	Low carbon steel (S10C) Surface roughness Ra=0.01 μ m
Mean hertzian contact pressure	approx. 581 MPa
Hertzian contact radius	approx. 0.1 mm

tribotester, steel disk and copper ball, which were attached to the pin top, were used. The disk surface was polished to afford a surface roughness less than Ra=0.01 μ m. The contact surface of the ball had a radius of 6.35 mm.

The test hydraulic oils were blends of base oil and additives. For base oil, a paraffinic mineral oil (density of 0.82 g/cm³ at 15 °C and dynamic viscosity of 7.12 cSt at 40 °C) was used, which is typically used for shock absorbers. The formulation of the test oils is listed in Table 2. ZnDTP and polyhydric alcohol ester were used as additives.

2.4 Indices for dynamic friction

In our previous study, four different friction characteristics were measured for hydraulic fluids and sliding materials (seal material and Cr plating) used in shock absorbers (Fig. 3) [12]. Summarizing the friction behavior under lubrication with four types of hydraulic fluids, we found (1) spike-like waveform when the motion stops or starts as the stroke reverses, (2) the speed-dependence of friction in the kinetic friction regime, and (3) amplitude-dependence of the friction force. Therefore, the conventional evaluation, which is solely based on the average friction force, is not sufficient for examining the effects of different friction behaviors on the shock absorber characteristics. Thus, the following three indices are proposed and used to analyze the dynamic friction characteristics, such that

Table 2 Formulation of test oils.

Additive	Additive (wt%)	
	ZnDTP	Polyhydric alcohol ester
Ad-1	0.0	0.0
Ad-2	0.5	0.0
Ad-3	1	0.0
Ad-4	2	0.0
Ad-5	4	0.0
Ad-6	0.0	0.5
Ad-7	0.0	1
Ad-8	0.0	2
Ad-9	0.5	2
Ad-10	1	2
Ad-11	2.0	2

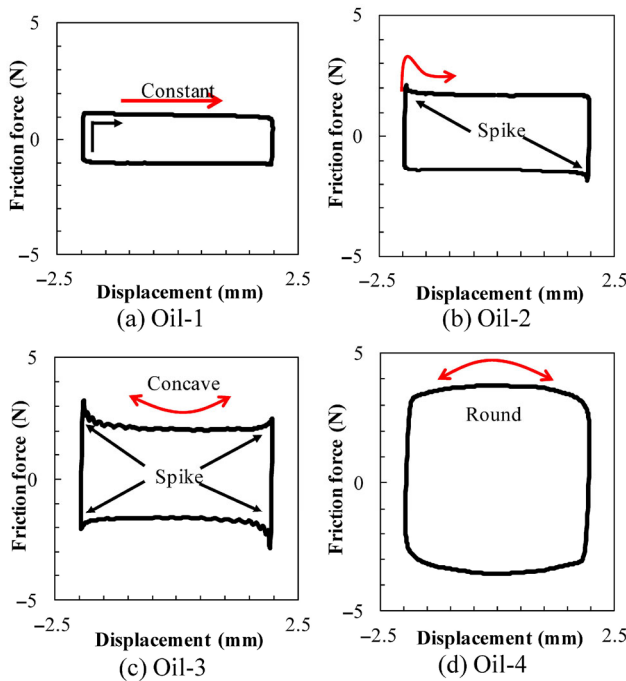


Fig. 3 Dynamic friction patterns measured using each lubricant at an amplitude of ± 2.0 mm: (a) Oil-1, (b) Oil-2, (c) Oil-3, and (d) Oil-4.

the dynamic friction characteristics can be extracted, quantified, and correlated with the shock absorber characteristics.

2.4.1 Spike index

“Spike index” is used to quantify the spike waveform that appears when the motion stops or starts as the stroke reverses. The spike waveform that appears immediately before motion stops, is not always identical to the spike waveform that appears when the motion starts again as the piston reverses direction; therefore, these are evaluated separately. Figure 4 shows the ranges over which the spike index is extracted in the time waveform of displacement and friction. We consider F_{sa} as the maximum friction from the beginning of motion to when the phase advances by $\pi/4$, i.e., from the top and bottom dead centers $\pi/2$ to $3\pi/4$, generalize its difference from the average friction force by dividing by the average, and further calculate the spike index on the acceleration side by using Eq. (1). Similarly, the range for the stopping case is $5\pi/4$ to $3\pi/2$, and the index is calculated using Eq. (2).

$$SI_a = (F_{sa} - F_{ave})/F_{ave}, \pi/2 \leq \theta \leq 3\pi/4 \quad (1)$$

$$SI_d = (F_{sd} - F_{ave})/F_{ave}, 5\pi/4 \leq \theta \leq 3\pi/2 \quad (2)$$

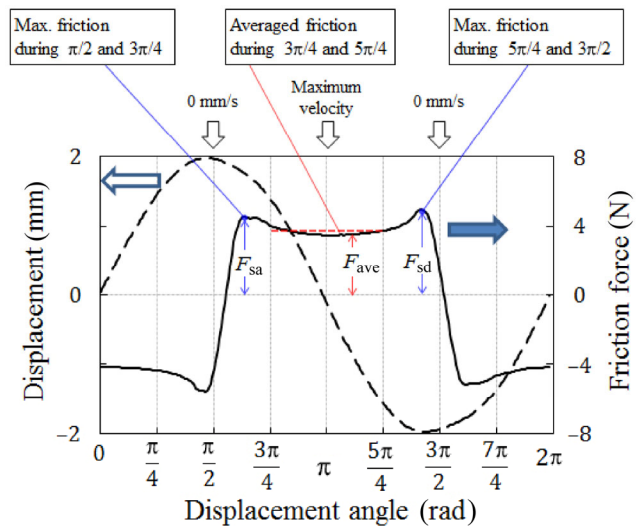


Fig. 4 Calculation concept of the spike index (SI).

Here, SI_a is the spike index on the accelerating side, SI_d is the spike index on the decelerating side, F_{sa} is the maximum friction force in the start-of-motion (accelerating) range where the displacement phase θ is between $\pi/2$ and $3\pi/4$, F_{sd} is the maximum friction force in the stopping (decelerating) range between $5\pi/4$ and $3\pi/2$, and F_{ave} is the average friction force between $3\pi/4$ and $5\pi/4$. For a larger spike index in the positive direction, a larger spike-like friction is observed; for a larger index in the negative direction, a slower onset of the friction force is observed.

2.4.2 Roundness index

The “roundness index” was utilized to quantify the speed characteristics of friction in the kinetic friction regime. With the maximum speed as the reference point, the speed characteristics can be different between the accelerating side and decelerating side; therefore, these were evaluated separately. Figure 5 shows the ranges of the displacement-friction time waveform used for evaluating the roundness index. The range between $3\pi/4$ and π is used before reaching maximum speed for the roundness index on the accelerating side, and that between π and $5\pi/4$ is employed for the decelerating side. The slope of friction force with respect to the changes in displacement is calculated using the least-squares method, as shown in Eqs. (3) and (4). The slope on the decelerating side is negative, such that for both acceleration and deceleration, the index is positive when the μ - V characteristics have a

positive slope with respect to the speed.

$$RI_a = \frac{\sum(F - \bar{F})(\theta - \bar{\theta})}{\sum(\theta - \bar{\theta})^2}, 3\pi/4 \leq \theta \leq \pi \quad (3)$$

$$RI_d = -\frac{\sum(F - \bar{F})(\theta - \bar{\theta})}{\sum(\theta - \bar{\theta})^2}, \pi \leq \theta \leq 5\pi/4 \quad (4)$$

Here, RI_a is the roundness index on the accelerating side, RI_d is the roundness index on the decelerating side, F is the friction force, \bar{F} is the average friction force, and θ is the displacement phase.

2.4.3 Amplitude-dependence index

The characteristics of friction (becoming small or large) for very small amplitudes are quantified as shown in Fig. 6, by using the “amplitude-dependence index”. As shown in Eq. (5), the maximum friction force at fine amplitude (± 0.1 mm) is divided by the average friction force at ± 2.0 mm to obtain the amplitude-dependence index.

$$AI = (F_{lm} - F_{ha}) / F_{ha} \quad (5)$$

Here, AI is the amplitude-dependence index, F_{lm} is the maximum friction force at the fine amplitude

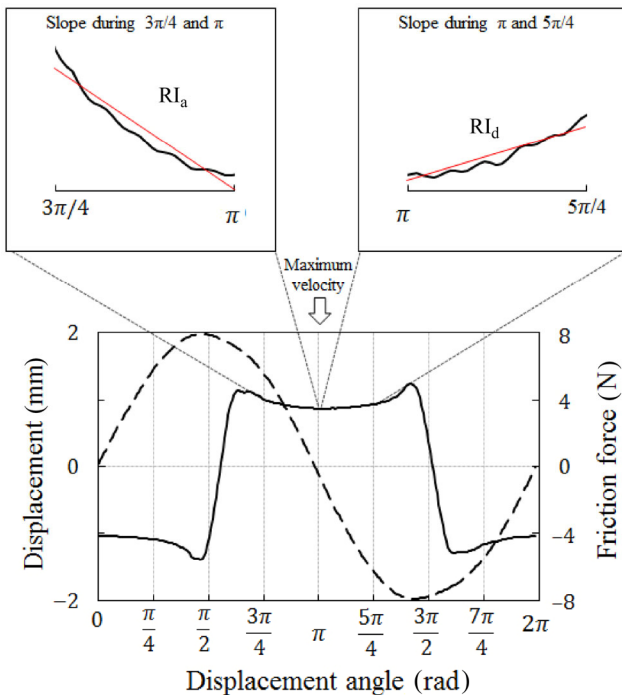


Fig. 5 Calculation concept of the roundness index (RI).

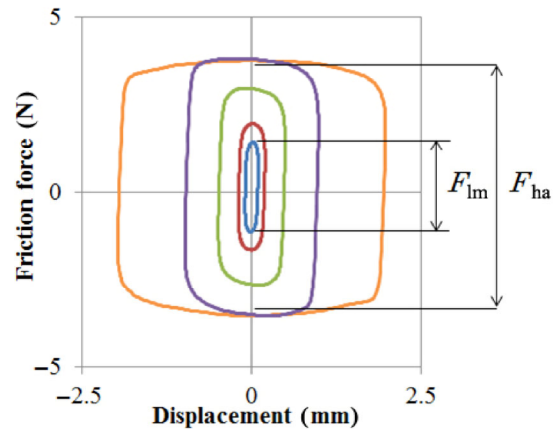


Fig. 6 Calculation concept of the amplitude index (AI).

(± 0.1 mm), and F_{ha} is the average friction force at amplitude ± 2.0 mm. The steady-state friction, F_{har} , is the average friction force at amplitude of ± 2.0 mm. Positive index value means that friction at the friction forces at the fine amplitude (± 0.1 mm) is larger than that of ± 2.0 mm amplitude, negative value means that friction force at fine amplitude is smaller than that of ± 2.0 mm amplitude, and 0 means they are identical.

2.5 Surface analysis

To understand the lubrication mechanism, optical microscopy (OM) and scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM/EDS) were performed for the disk surface after the tribo-test. For the surface analysis, steel disk specimens were rubbed against the copper ball under lubrication with hydraulic oils at amplitudes of ± 2.0 and ± 0.1 mm.

3 Results and discussion

3.1 Friction characteristics

The measured friction waveforms are illustrated in Fig. 7. Figures 8–10 show the average friction coefficient, the amplitude dependence index, and the spike index with the additive amount as the horizontal axis.

Compared to the base oil, the average friction decreased for the ester at amplitude of ± 2.0 mm, but it did not decrease at the fine amplitude of ± 0.1 mm. For both the ester and ZnDTP, the spike waveforms became smaller as the amount of additives increased. The amplitude-dependence index showed the most prominent features. For the base oil and the base oil

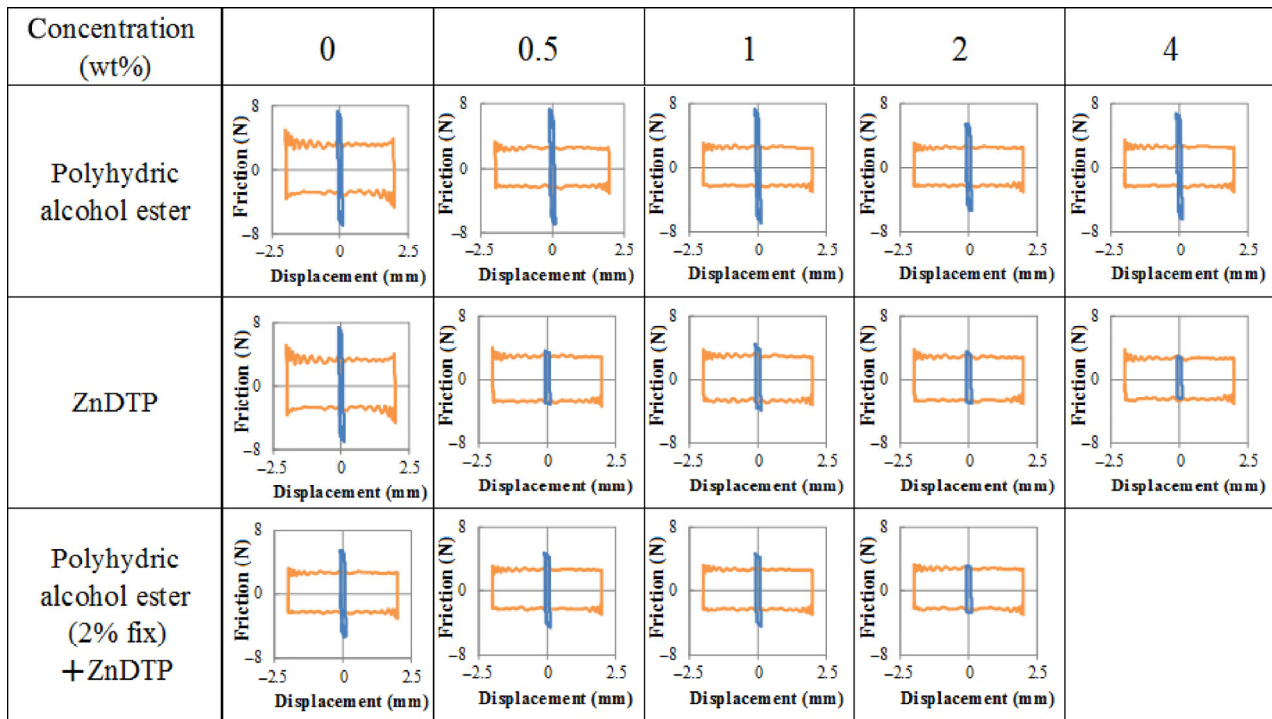


Fig. 7 Friction waveform results for each hydraulic fluid.

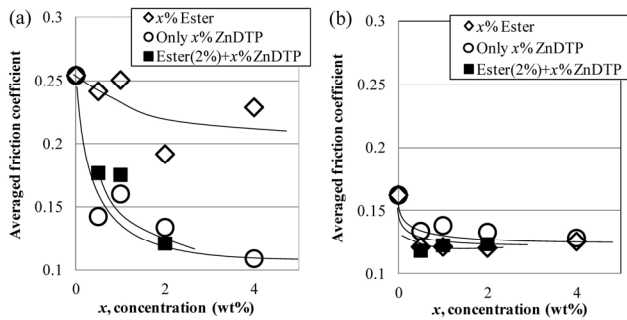


Fig. 8 Correlation between additive concentration and averaged friction coefficient at (a) 3.14 mm/s and (b) 62.8 mm/s.

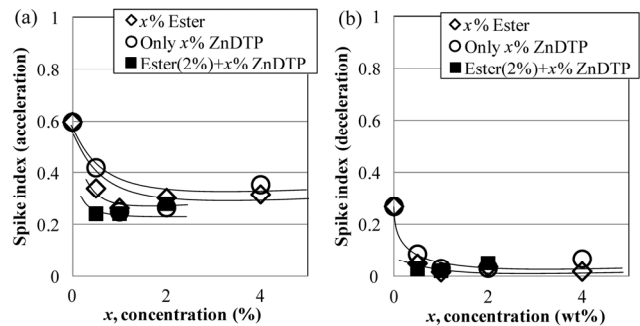


Fig. 10 Correlation between additive concentration and spike index (SI) at 62.8 mm/s: (a) acceleration and (b) deceleration.

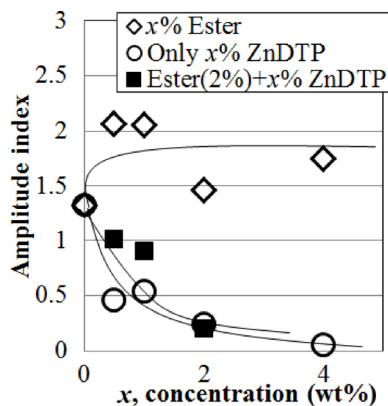


Fig. 9 Correlation between additive concentration and amplitude index (AI).

containing only the ester additive, the friction increased by a factor of approximately 1.5 to 2 at amplitude of ± 0.1 mm, compared to that at ± 2.0 mm. By adding ZnDTP and the ester with ZnDTP, the value of the amplitude-dependence index became smaller at amplitude of ± 0.1 mm. These results reveal that lubrication can be obtained at amplitude of ± 2.0 mm with the ester or ZnDTP additive, but at amplitude of ± 0.1 mm, there is insufficient lubrication for the ester-only additive and low-concentration ZnDTP, and the friction force becomes large. In the sliding combination of copper and steel, the roundness index was almost zero under any sliding condition.

3.2 Sliding surface analysis

For the base oil (Ad-1), base oil+ZnDTP (Ad-2, Ad-5), base oil+ester (Ad-8), and base oil+ester with ZnDTP (Ad-10), distinctive results for friction with respect to amplitude and additive concentration were obtained. Figure 11 shows the OM image, Cu mapping energy dispersive X-ray spectrometry (EDS) image, and quantitative analysis results. Component mapping images were obtained at an accelerating voltage of 10 kV. The quantitative analysis data were collected at the non-sliding part (P1), sliding regions, and at

± 0.1 mm (P2) and ± 2.0 mm (P3) amplitudes. In the EDS analysis data, the zinc and copper peaks were partially overlapped; therefore, these results were omitted.

The sliding surfaces with Ad-1 (the base oil) became black, owing to the presence of oxygen and resulting oxidation. At the fine amplitude of ± 0.1 mm, the results showed significant transfer of copper. For the oxide films produced by sliding, the friction increases at fine amplitudes and the spike indices are large.

For Ad-4 (2% ester), slight oxidation and Cu transfer were observed, and the lubrication due to the additive

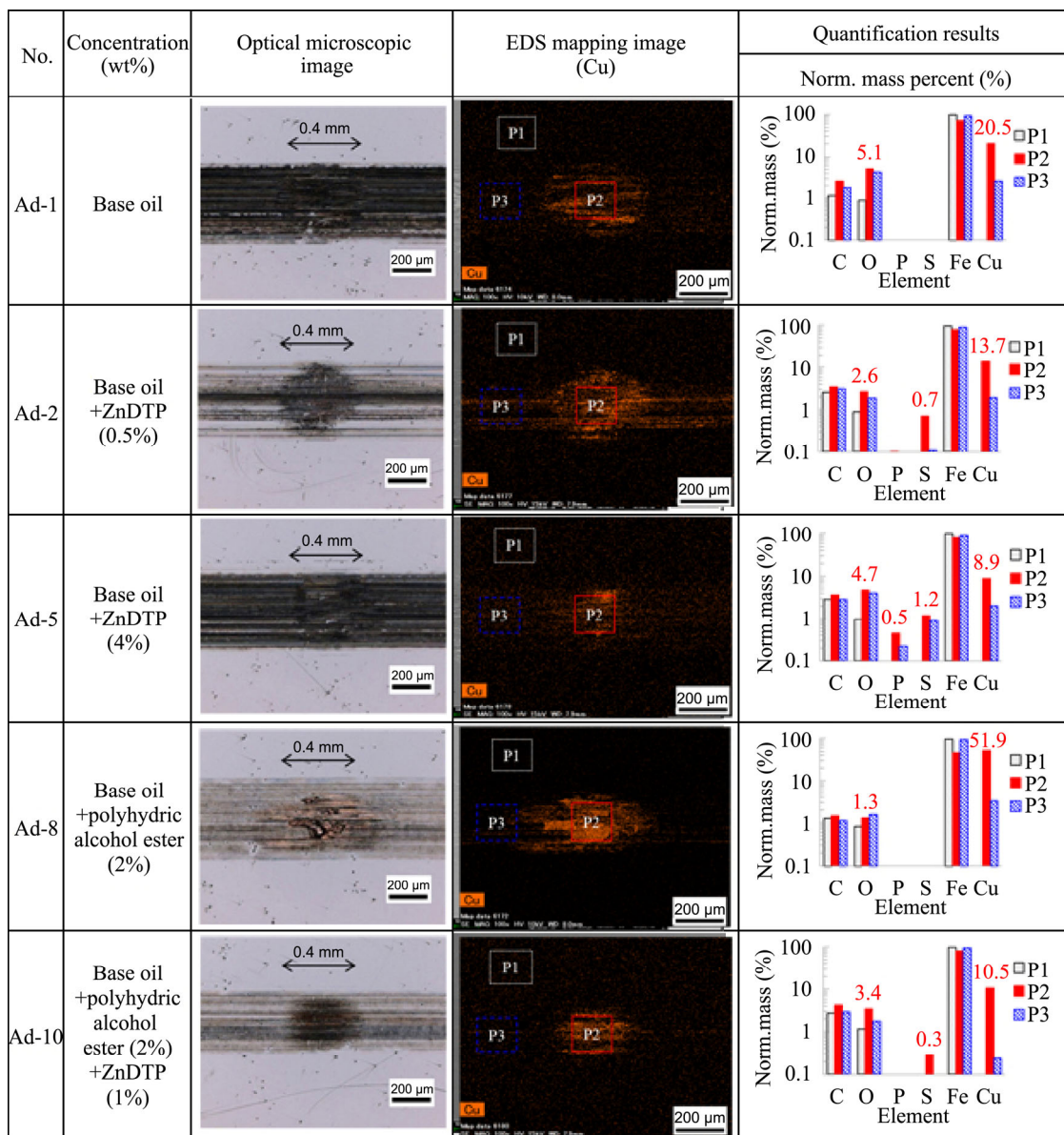


Fig. 11 Results of sliding surface observation and analysis.

appeared to be maintained, but elements on the sliding surfaces as surface reaction films could not be clearly identified. This suggested that the lubrication was maintained by the adsorption films of the organic material. However, with fine amplitudes, substantial Cu transfer was observed, and the amplitude-dependence index was large. Therefore, it was speculated that the direct contact between the sliding materials increased in boundary lubrication.

With AD-5 (4% ZnDTP), slight Cu transfer was observed for both ± 0.1 and ± 2.0 mm amplitudes. Throughout the sliding surface, sulfur and phosphorus from ZnDTP were detected. Even at an amplitude of ± 0.1 mm, Cu transfer was suppressed. Therefore, it was speculated that the lubrication occurred by the formation of tribo-films formed by the presence of ZnDTP at the sliding surface. Ad-6 (0.5% ZnDTP), compared to AD-5 (4% ZnDTP), had less sulfur and zinc reaction film formed by ZnDTP, and more Cu transfer. This result also suggests that the formation of reaction film at the sliding part maintains the

lubrication at fine amplitudes. For Ad-10 (2% ester + 1% ZnDTP), at both fine amplitudes of ± 0.1 and ± 2.0 mm, slight Cu transfer as well as slight sulfur and zinc transfer due to ZnDTP were observed. This suggests that by adding the ester and ZnDTP simultaneously, the lubrication at fine amplitudes is maintained by organic adsorption films, without the formation of reaction films.

Figure 12 shows the results of using dynamic friction indices to study the characteristics of Cu and a steel plate, and analysis of their surfaces after sliding. The friction characteristics of the Cu ball and steel have a distinct feature; the lubrication state changes depending on the amplitude condition. On the basis of the surface analysis results, it was determined that the performance depended on whether a reaction or adsorption film formed by the additive was maintained. With the ester additive exclusively, the lubrication occurs due to the formation of an adsorption film [13, 14], and at fine amplitudes, the lubrication is insufficient and the friction increases. For lubrication with ZnDTP, a reaction

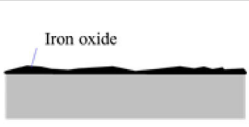
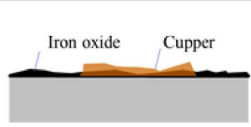
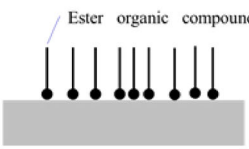
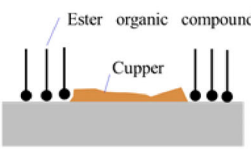
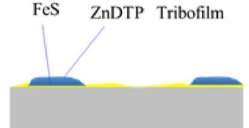
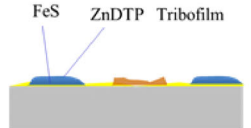
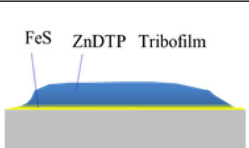
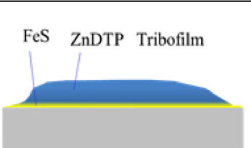
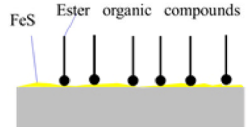
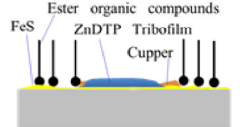
Hydraulic fluid composition	Large amplitude (4 mm)	Small amplitude (0.2 mm)
Base oil		
Polyhydric alcohol ester (2%)		
ZnDTP (0.5%)		
ZnDTP (4.0%)		
Polyhydric alcohol ester (2%) + ZnDTP (1%)		

Fig. 12 Summary of the results of surface analysis after sliding.

film of sulfur and phosphorus is formed on the surface due to the additive [15, 16], and for more than 0.5 to 1% additive, lubrication is maintained at fine amplitudes. By adding both the ester and ZnDTP, a reduced reaction film formation is observed, and the lubrication is maintained even at fine amplitudes via the formation of the adsorption film. ZnDTP forms a tribo-film even in large amplitude and fine amplitude regions. These results indicate that ZnDTP (Figs. 8(a) and 8(b)) produces reaction tribo-film due to frictional heat [17]. Therefore, when the additives are mixed, ester lubrication occurs at large (± 2.0 mm) amplitudes, and the temperature increases at low amplitudes, when reaction film lubrication by ZnDTP possibly occurs. On the basis of these results, it is concluded that when the ester and ZnDTP are blended together, the lubrication is maintained with tribo-films covering the sliding surface, i.e., the organic adsorption film and the reaction film of ZnDTP are formed at large and fine amplitudes, respectively.

4 Conclusions

To determine the effects of dynamic friction characteristics on the performance of shock absorbers, we developed a device that can measure the speed dependence of friction at high precision and examined the evaluation indices to extract the features of dynamic friction characteristics.

- (1) The friction characteristics of a Cu ball and steel are such that with an ester additive exclusively, insufficient lubrication at the fine amplitude of ± 0.1 mm is observed, and the friction increases.
- (2) For lubrication using ZnDTP, the reaction films of sulfur and phosphorus are formed on the surface because of the additive, and for more than 0.5% to 1% additive, lubrication is maintained in the fine amplitude condition.
- (3) By adding both the ester and ZnDTP, a slight formation of reaction films is observed, and lubrication at the fine amplitude condition is maintained owing to the formation of adsorption films.

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