

Friction and Wear Characteristics of Advanced Space Lubricants

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The performance of a variety of space lubricants was compared under boundary lubrication at ground level. The types of lubricants studied were the two synthetic base oils PFPE 815Z and MAC 2001A and the two greases 601EF and R2000. High-pressure rheological tests were performed in order to characterize the behavior of each base oil as a function of pressure and temperature. The effect of base oils and greases on friction and wear was studied using Soda-type four-ball tribometer. The highest wear scar was found for 815Z, but it showed the lowest coefficient of friction, whereas 601EF (containing a rust and corrosion inhibitor blended with base oil 815Z), base oil 2001A, and grease R2000 blended with base oil 2001A showed lower wear scars, but produced higher friction coefficients. This unique phenomenon of 815Z was investigated from the phase diagram of 815Z. Investigating these phenomena, the authors found that the decomposition of base oil 815Z containing the acetal group (-OCF₂O-) occurred by mechanical shear at high shear rates in the elastic-plastic solid. Hydrogen fluoride is released from the decomposition of acetal groups within the fluoropolymer. As a result, the generation of hydrogen fluoride increased the wear rate of the 815Z base oil. Grease 600EF (formulated without the rust and corrosion inhibitor) and 602EF (containing a molybdenum disulfide) blended with base oil 815Z were also studied.

KEY WORDS

Tribology; Space Lubricant; Friction; Wear

INTRODUCTION

Liquid lubricants are frequently used in space mechanisms because they are associated with low mechanical noise, no wear in the elastohydrodynamic regime, ease of replenishment, ability to remove wear debris, and insensitivity to environmental factors (Jones, et al. (1), Jones (2)). Friction and wear behav-

ior of space lubricants are vital under boundary lubrication condition for longevity of space mechanisms. Perfluoropolyethers (PFPEs) and multiply alkylated cyclopentane (MAC) are well-known liquid lubricants for space applications (Bair, et al. (3), Nélias, et al. (4)). Also, greases formulated from these base oils are used (Gschwender, et al. (5), Oswald, et al. (6)). In this study, the authors considered two kinds of base oils (PFPE 815Z and MAC 2001A) and four kinds of greases (600EF, 601EF, 602EF, and R2000). The greases were 600-class greases (600EF, 601EF, and 602EF) formulated with base oil 815Z and thickened with lubrication grade polytetrafluoroethylene (PTFE) particles and grease R2000 formulated with base oil 2001A and thickened with a sodium complex soap.

A previous investigation's article by the current authors presented the results of bearing-fatigue life tests in the two synthetic base oils (815Z and 2001A) and two greases (601EF and R2000) (Ohno, et al. (7)). The most significant conclusions are as follows: the permanent viscosity loss at high Hertzian pressure under EHL conditions and the hydrogen fluoride generation shortened bearing life with the 815Z base oil. In the case of grease 601EF with base oil 815Z, the permanent viscosity loss did not occur in ball bearings, and the bearing life was extended.

The authors also previously investigated the effect of mean Hertzian pressure on the permanent viscosity loss under EHL conditions of base oil 815Z (Mia, et al. (8), Ohno (9)). They found that the permanent viscosity loss of 815Z occurred rapidly with time at a mean contact pressure of 1.95 GPa to 2.67 GPa. When the mean contact pressure decreased, the degree of viscosity loss decreased gradually, and there was no permanent viscosity loss at a mean contact pressure of 0.41 GPa. Therefore, the permanent viscosity loss appears to increase with the change of phase from liquid to solid under EHL conditions. However, friction and wear characteristics of these advanced space lubricants under the boundary lubrication condition at high contact pressure are not clear. The purpose of this article is to clarify the tribological behavior of advanced space lubricants under boundary lubrication conditions.

In the current research, the friction and wear behavior of two synthetic base oils (PFPE 815Z and MAC 2001A) and the two greases (601EF and R2000) are examined using a four-ball wear

TABLE 1—PROPERTIES OF BASE OIL

Fluid Name	ρ , g/mL 15°C	ν , mm ² /s		VI	M g/mol
		40°C	100°C		
815Z	1.8580	139.1	42.7	343	9200
2001A	0.8513	103.2	14.4	137	910

test machine at atmospheric conditions. Greases 600EF (without the usual rust and corrosion inhibitor) and 602EF (containing molybdenum disulfide) blended with base oil 815Z were also studied.

PROPERTIES OF BASE OILS AND GREASES

The base oils used in this study are PFPE 815Z of Lot 3206OP and MACs 2001A of Lot MI050614. Properties appear in Table 1, where ρ = density (g/mL), ν = kinematic viscosity (mm²/s), VI = viscosity index, and M = molecular weights. Table 2 shows the compositions and properties of the greases in the study: greases 600-class (600EF of Lot 69846, 601EF of Lot 101038 (containing rust and corrosion inhibitor) and 602EF of Lot 125940 (containing molybdenum disulfide 5 wt%) formulated with base oil 815Z and thickened with PTFE particles, and grease R2000 of Lot SA050120 formulated with base oil 2001A and thickened with the sodium complex soap. The authors previously used the two synthetic base oils (815Z and 2001A) and two greases (601EF and R2000) for ball-bearing fatigue life test (Ohno et al. (7)).

HIGH-PRESSURE RHEOLOGY OF BASE OILS 815Z AND 2001A

Viscoelastic Solid Transition Temperature at Atmospheric Pressure

Experimental setup for the measurement of viscoelastic solid transition temperature at atmospheric pressure T_{VE0} is shown in Fig. 1(a). When a minute air bubble is closed into a space between test fluid and a cover glass plate, its volume apparently expands as a result of contraction of the fluid by cooling. Figure 1(b) represents the experimental view of MAC 2001A with air bubble at the beginning of measurement. Thus, the expanded bubble generates tensile stresses along its interface under solidified condition. At the same time the photoelastic effect appears under a dark polarized field as shown in Fig. 1(c). This enables the stress analysis and estimation of mechanical properties of the solidified fluid (Ohno, et al. (10)). The temperature where this photoelastic effect appears at dark polarization is known as *viscoelastic solid transition*

TABLE 2—PROPERTIES OF GREASE

Grease Name	Base Oil	Grease Thickener	Penetration,	
			Worked	Additive
600EF	815Z	PTFE	288	—
601EF	815Z	PTFE	287	R.I & C.I
602EF	815Z	PTFE	273	MoS ₂
R2000	2001A	Sodium complex soap	276	—

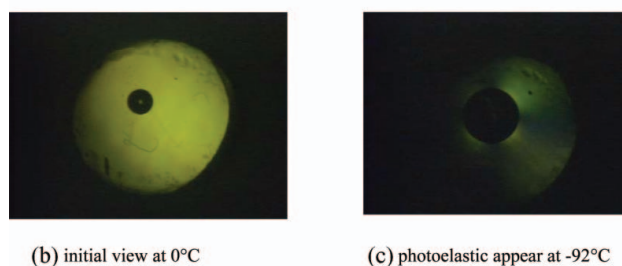
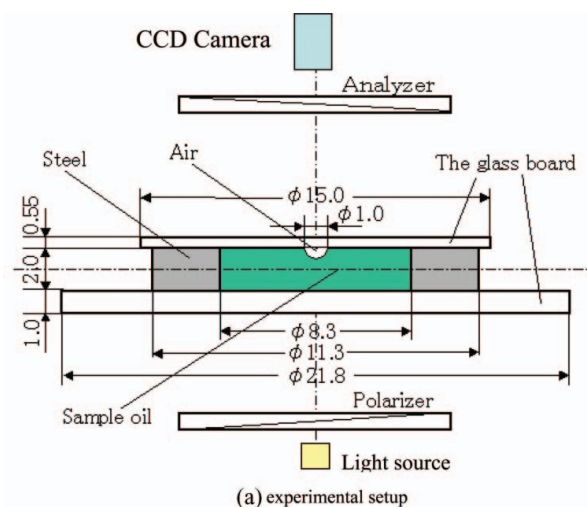


Fig. 1—Experimental view of T_{VE0} for Fluid 2001A. (Figure available in color online.)

temperature at atmospheric pressure. Determined T_{VE0} are given in Table 3. The accuracy of the T_{VE0} measurement is estimated at $\pm 2^\circ\text{C}$.

Viscoelastic Solid Transition Temperature at High Pressure and Bulk Modulus

The measurement of high-pressure density was done by the high-pressure densitometer (Ohno, et al. (11)). The test fluid of 2 mL was poured into the test machine, and pressure was applied in the upper plunger by a hydraulic power unit. The density was determined corresponding to pressure by measuring the fluid volume in the machine using a linear gauge. Isothermal compressibility influence was considered in the experiment. One of the basic equations for the solidification of oils is the equation

TABLE 3—PARAMETERS FOR PHASE DIAGRAM OF EQ. [2]

Variable	815Z	2001A
-13°C	0.75 GPa	0.64 GPa
-5°C	0.85 GPa	—
0°C	0.89 GPa	0.74 GPa
20°C	—	0.93 GPa
T_{VE0}	-106°C	-92°C
$A_1, ^\circ\text{C}$	1626	489
A_2, GPa^{-1}	0.075	0.279

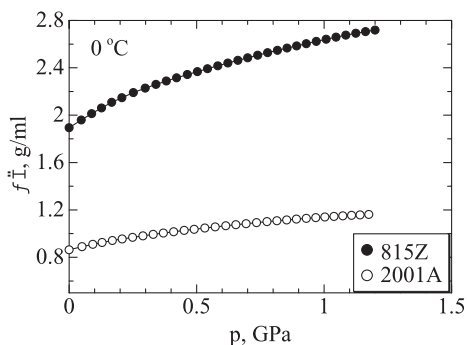


Fig. 2—Density ρ (g/mL) – pressure p curves of base oil 815Z and 2001A

of volumetric change, which is used in the strength of materials (Ohno and Hirano (12)). The volumetric strain ε is defined as the ratio of the decrease in volume to the original volume:

$$\varepsilon = \frac{dV}{V} = \left(-\frac{\partial \ln \rho}{\partial p} \right)_T dp + \left(-\frac{\partial \ln \rho}{\partial T} \right)_P dT = \left(-\frac{1}{K} \right) dp + 3\delta dT, \quad [1]$$

where V is volume, ρ is density, p is pressure, T is temperature, K is tangent bulk modulus, and δ is coefficient of thermal expansion.

The change in density ρ against pressure at 0°C of 815Z and 2001A is shown in Fig. 2. Differentiating the pressure-density curve, the tangent bulk moduli $K = (\partial \ln \rho / \partial p)^{-1}$ are estimated as shown in Fig. 3. The tangent bulk modulus is estimated to $\pm 5\%$. The viscoelastic solid transition point p_{VE} is obvious from the abrupt change of dK/dp in Fig. 3. For 815Z the viscoelastic transition point p_{VE} is 0.85 GPa, and p_{VE} of 2001A is 0.75 GPa. The viscoelastic transition pressure p_{VE} at each temperature of 815Z and 2001A is listed in Table 3. The transition pressure and temperature are measured to $\pm 5\%$ and $\pm 1^\circ\text{C}$, respectively.

Phase Diagram

The phase diagrams of 815Z and 2001A are shown in Fig. 4 and the equation related to the temperature–pressure of viscoelastic solid point T_{VE} is represented in the following empirical formula (Yasutomi, et al. (13))

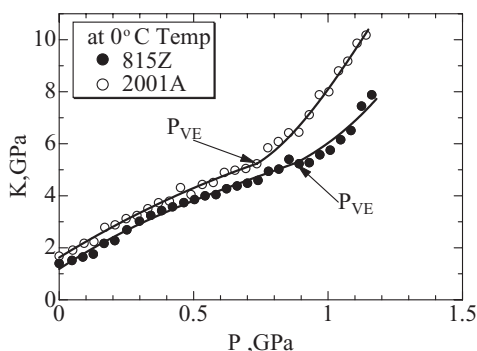


Fig. 3—Relationship between tangent bulk modulus K and pressure p of base oil 815Z and 2001A, p_{VE} : viscoelastic solid transition pressure at temperature T .

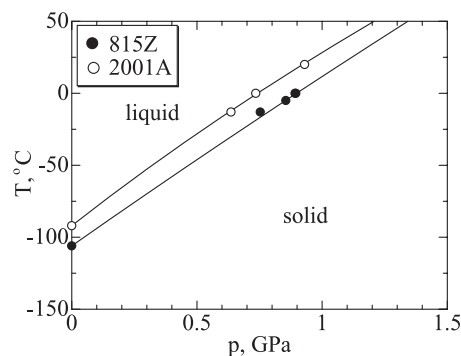


Fig. 4—Phase diagrams of base oil 815Z and 2001A.

$$T_{VE} = T_{VE0} + A_1 \ln(1 + A_2 p), \quad [2]$$

where A_1 and A_2 are parameters related to fluid properties. The phase diagram data and parameters obtained are listed in Table 3.

Viscosity–Pressure–Temperature Relationship

A high-pressure viscometer of the falling-ball type designed at Saga University was utilized for the viscosity measurement at pressures up to 0.33 GPa, absolute viscosities up to 10^3 Pa-s, and temperatures from -10°C to 80°C . Barus’s pressure–viscosity coefficient α and the reciprocal asymptotic pressure α^* was derived using the least squares method. The pressure–viscosity coefficient α (GPa^{-1}) and the reciprocal asymptotic pressure α^* (GPa^{-1}) (Blok (14)) are given in Table 4. The reciprocal asymptotic pressure α^* (GPa^{-1}) of 815Z at 0°C has been previously reported by Bair (15). α^* value of Bair is 21.8 GPa^{-1} , and our data is $\alpha^* = 24.0 \text{ (GPa}^{-1})$. The variations of the pressure–viscosity coefficient α and the reciprocal asymptotic pressure α^* with viscosity are described by the equation

$$\alpha = C_1 + C_2 \log_{10} \nu, \quad [3]$$

where ν is kinetic viscosity in mm^2/s and α is pressure–viscosity coefficient in GPa^{-1} . The parameters C_1 and C_2 are shown in Table 4. In the case of 815Z, the experimental value of α is

TABLE 4—PRESSURE–VISCOSITY COEFFICIENT α AND RECIPROCAL ASYMPTOTIC PRESSURE α^* OF BASE OIL

Variable	815Z		2001A	
	$\alpha \text{ GPa}^{-1}$	$\alpha^* \text{ GPa}^{-1}$	$\alpha \text{ GPa}^{-1}$	$\alpha^* \text{ GPa}^{-1}$
-10°C	20.9	25.4	22.5	26.5
0°C	19.4	24.0	20.1	24.1
20°C	16.5	21.6	16.1	20.0
40°C	14.5	19.6	13.5	16.6
60°C	12.9	17.9	10.7	13.8
80°C	12.1	16.4	9.2	11.4
C_1	-4.06	0.87	0.11	1.60
C_2	8.81	8.74	6.52	7.33

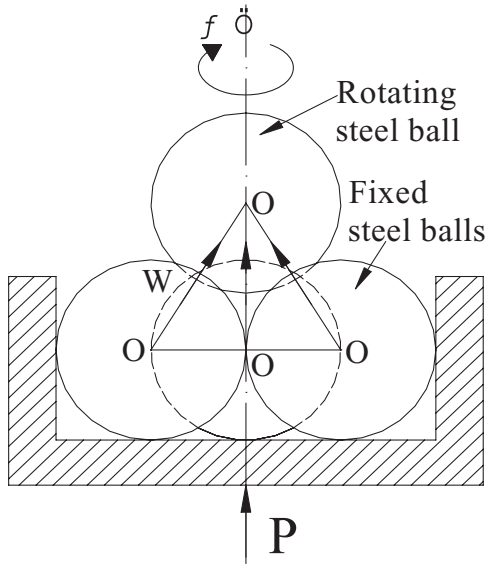


Fig. 5—Main part of four-ball test apparatus.

19.4 (GPa)^{-1} , and the predicted value of α from Eq. [3] is 19.3 (GPa)^{-1} at 0°C and $\nu = 444 \text{ mm}^2/\text{s}$.

FOUR-BALL WEAR TEST

Experimental Apparatus and Method

Friction and wear experiments were carried out using a conventional four-ball wear tester. The arrangement of the test balls is shown in Fig. 5. Bearing-steel balls of 19.05 mm in diameter and 5.7 nm in mean surface roughness were used. All experiments were conducted at load 1.39 kN and at upper rotating ball speed 60 rpm, corresponding to a sliding speed of 0.035 m/s. Duration for each experiment was 1 h, and thus total sliding distance was 124.6 m. Load for each pair was 564 N, corresponding mean Hertzian pressure = 2.6 GPa, and Hertzian diameter $d_H = 0.521 \text{ mm}$. Friction was measured by means of a torsion bar to which the bottom of the oil container was clamped. Experiments were carried out at room temperature.

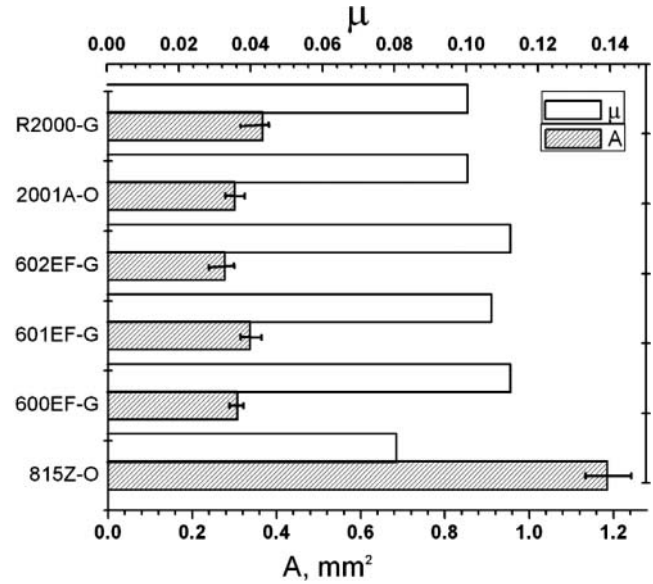


Fig. 7—Relation of wear scar area A and friction coefficient μ .

EXPERIMENTAL RESULTS AND DISCUSSIONS

The photograph of wear scar of all tested samples is shown in Fig. 6(a)–(f), labeling base oil as O and grease as G. The wear scar area A calculated from mean wear scar diameter of fixed balls and the friction coefficient μ at 60 min of test are plotted in Fig. 7. Wear scar areas for the three fixed balls are different, as indicated by error bars in the figure. Error bars also used in other related figures. The area A of wear scar becomes larger in the order 602EF-G, 2001A-O, 600EF-G, 601EF-G, R2000-G, and 815Z-O; and the friction coefficient μ is smaller in the order 602EF-G, 600EF-G, 601EF-G, 2001A-O, R2000-G, and 815Z-O. The results indicate an inverse relationship between the area of the wear scar and the coefficient of friction. To mention particular features from Fig. 6 and Fig. 7, the wear scar area of base oil 2001A decreased 22% compared with grease R2000 formulated with base oil 2001A. On the other hand, the wear scar area of the base oil 815Z increased about 400% in comparison with greases 600EF-G, 601EF-G, and 602EF-G formulated with base oil 815Z.

The mechanism of breakdown of the lubricant film in a concentrated steel contact has been established by the International Research Group on Wear of Engineering Materials OECD (Begelinger and de Gee (16)). Begelinger and de Gee (17) pointed out about the elastohydrodynamic (EHD) action in the low-speed region that, even at the lower speed of 0.0007 m/s, the load-carrying capacity of the contact still depends strongly on lubricant viscosity. According to Hamrock and Dowson (18), if the material, load, and speed remain the same, EHD oil film thickness at center is only proportional to $\eta^{0.67}$ and $\alpha^{0.53}$, where η = absolute viscosity, and α = pressure–viscosity coefficient. The power series of η and α is almost the same. Therefore, the lubricant parameter $\alpha\eta$ (Sharma, et al. (19)) is used to draw an important relationship with EHD central film thickness even at the lower speed. The authors have previously indicated that the wear scar area A of same group oil decreases with increase in $\alpha\eta$

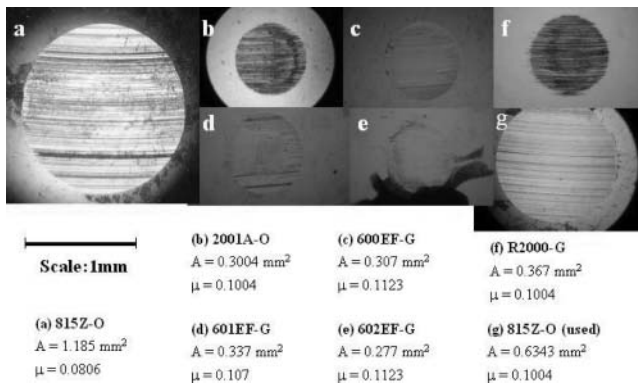


Fig. 6—Wear scars of fixed steel ball in four-ball test.

gradually (Ohno, et al. (20)). Therefore, the lubricant parameters $\alpha\eta$ of 815Z and 2001A at four-ball wear testing condition were calculated. The absolute viscosity η , the pressure–viscosity coefficient α , and the product $\alpha\eta$ of the base oil 815Z at 20.2°C are $\eta = 0.437$ Pa·s, $\alpha = 17.0$ GPa⁻¹, and $\alpha\eta = 7.43$ ns, respectively. The base oil 2001A at 21.2°C has $\eta = 0.233$ Pa·s, $\alpha = 16.5$ GPa⁻¹, and $\alpha\eta = 3.85$ ns. The lubricant parameter $\alpha\eta$ of 815Z is larger than that of 2001A. The wear scars of base oil 815Z shown in Fig. 6 and Fig. 7 cannot be explained from the lubricant parameter $\alpha\eta$.

A previous investigation by the current authors presented the results of bearing-fatigue life tests in the two synthetic base oils (815Z and 2001A) and two greases (601EF and R2000; Ohno, et al. (7)). The most significant conclusions were as follows: the permanent viscosity loss at high Hertzian pressure under EHL conditions and the hydrogen fluoride generation shortened bearing life with the 815Z base oil. Namely, the decomposition of base oil 815Z containing the acetal group (-OCF₂O-) (Mori and Morales (21)) occurred by mechanical shear at high shear rate under the severe EHL condition. Hydrogen fluoride is released with the decomposition of acetal group.

The authors also previously investigated the effect of mean Hertzian pressure on the permanent viscosity loss under EHL conditions of base oil 815Z (Mia, et al. (8)). They found that the permanent viscosity loss of 815Z occurred rapidly with time at a mean contact pressure of 1.95 to 2.67 GPa. When the mean contact pressure decreased, the degree of viscosity loss decreased gradually, and there was no permanent viscosity loss at a mean contact pressure of 0.41 GPa. Therefore, the permanent viscosity loss appears to increase with the change of phase from liquid to solid under EHL conditions. Therefore, the cause of the wear scar of base oil 815Z was examined from the permanent viscosity loss and the hydrogen fluoride generation.

In order to investigate the effect of permanent viscosity loss of base oil 815Z on the wear scar area, the four-ball wear test of the base oil 815Z that made the permanent viscosity loss in the bearing-life test of the operation time 85.5 h (Ohno, et al. (7)) was also done. The properties of used oil 815Z are viscosity of 62.31 mm²/s at 40°C and 19.47 mm²/s at 100°C. The absolute viscosity η and pressure–viscosity coefficient α of used oil 815Z at 28.3°C are $\eta = 0.156$ Pa·s, $\alpha = 13.6$ GPa⁻¹, and lubricant parameter $\alpha\eta = 2.12$ ns. The photograph of the wear scar of used oil 815Z is in Fig. 6(g). Though lubricant parameter $\alpha\eta$ of used oil 815Z is smaller than fresh oil 815Z with $\alpha\eta = 7.43$ ns, the wear scar area of used oil 815Z as shown in Fig. 6(g) is about one half of wear scar area of fresh oil 815Z as shown in Fig. 6(a). The big wear scar of base oil 815Z as shown in Fig. 6 and Fig. 7 cannot be explained only from decreasing lubricant parameter $\alpha\eta$ with permanent viscosity loss. Therefore, the wear scar of base oil 815Z was probably caused by hydrogen fluoride generation with permanent viscosity loss similar to bearing-fatigue test (Ohno, et al. (7)).

Next, the authors considered the cause of the small wear scar area of greases 600EF, 601EF, and 602EF formulated with base oil 815Z. Ohno, et al. (7) pointed out that the permanent viscosity loss of base oil 815Z did not occur in thrust ball bearings in the case of the grease 601EF formulated with base oil 815Z, and the thickener PTFE of grease 601EF has

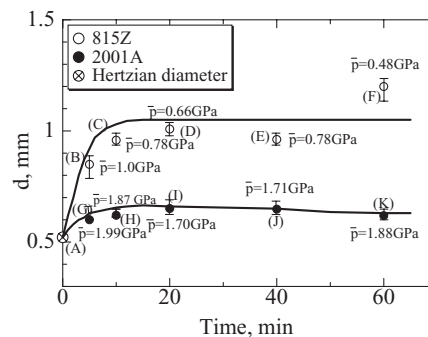


Fig. 8—Time dependents of wear scar for base oil 815Z and 2001A.

antidecomposition action of base oil 815Z. This is the main possible cause of larger wear scar for the base oil 815Z than the formulated greases. In addition, the effect of additive for wear was examined. Grease 600EF is straight grease, grease 601EF has usual rust inhibitor and corrosion inhibitor, and grease 602EF contains a molybdenum disulfide 5 wt%. Grease 602EF showed smaller wear scar area due to the effect of molybdenum disulfide.

Wear behavior of the base oils 815Z and 2001A are again investigated using the applied average pressure on the wear rate. Figure 8 shows the time dependence of wear scar for the base oils mentioning the average pressure of each experimental point. Here, average pressure \bar{p} was calculated from the applied load over the wear scar area. It is found that the wear is dependent on the operating time and the type of base oil. Whereas the wear scar of the steel ball in base oil 2001A is nearly constant with the operating time, the wear scar of the steel ball in base oil 815Z increases at an early stage of operating time. The high wear rate of the steel ball in the base oil 815Z at an early stage seems to be correlated with the corrosion reaction of the steel ball in base oil 815Z.

The authors also previously investigated the effect of mean Hertzian pressure on the permanent viscosity loss under EHL conditions of base oil 815Z (Mia, et al. (8)). The most significant conclusions are as follows: the occurrences of the permanent viscosity loss and the hydrogen fluoride occur in viscoelastic solid and elastic–plastic solid of base oil 815Z at high pressure. The experimental points in Fig. 8 are replotted on the phase diagram in Fig. 4 as shown in Fig. 9. In the base oil 815Z, Fig. 9 shows as solid in the initial experimental condition of mean Hertzian pressure at point (A). The mean pressure decreases when the wear progresses with the operating time as shown in Fig. 8. And the experimental conditions of points (B) to (F) are within liquid at Fig. 9. The mechanism of wear of steel ball in base oil 815Z is deduced to be as follows. The mean pressure at an early stage of wear test is large, the base oil 815Z at that condition has solid state, and therefore the hydrogen fluoride generation with permanent viscosity loss occurs much as in bearing fatigue test (Ohno, et al. (7)). The hydrogen fluoride brings corrosive wear, and the high wear rate of the steel ball in base oil 815Z arises as shown in Fig. 8. The high wear rate of corrosive wear has been obtained for the wear of steel in gasoline–ethanol–water mixtures (Yahagi

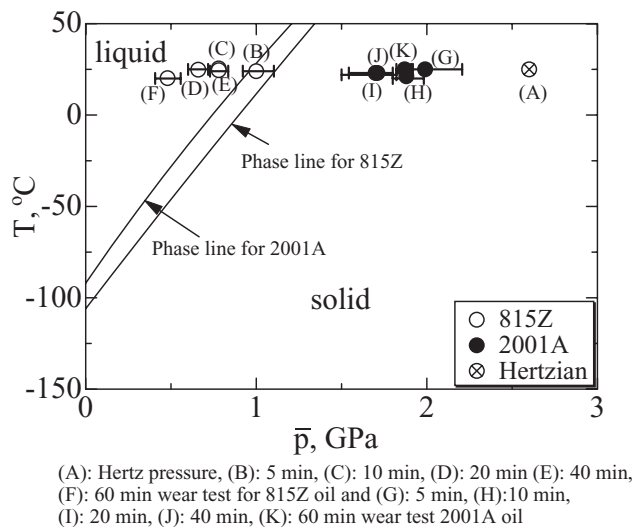


Fig. 9—Experimental points in phase diagram of base oil 815Z and 2001A.

and Mizutani (22)). Therefore, the small wear scar shown in Fig. 6 and Fig. 7 for greases 600EF, 601EF, and 602EF formulated with base oil 815Z and thickened with a microcolloid dispersion of tiny PTFE is considered to be prevention action of decomposition of base oil 815Z by thickener PTFE similar to that in bearing-fatigue test (Ohno, et al. (7)).

Next, we considered the cause of the lower friction coefficient of base oil 815Z with increasing wear scar area as shown in Fig. 6 and Fig. 7. Figure 10 shows the relation between friction coefficient μ and the operating condition $T_{VE} - T$ for the wear test of base oils 815Z and 2001A as shown in Fig. 8, where T_{VE} is the viscoelastic solid transition temperature at pressure p calculated from Eq. [2], and T is oil temperature. Therefore, the lubricating oil has liquid at $T_{VE} - T < 0$ condition, and $T_{VE} - T > 0$ condition has solid. A significant correlation exists between friction coefficient μ and operating condition $T_{VE} - T$: greater $T_{VE} - T$ indicates greater friction coefficient μ . In other words, the results indicated that friction coefficient μ under boundary lubrication

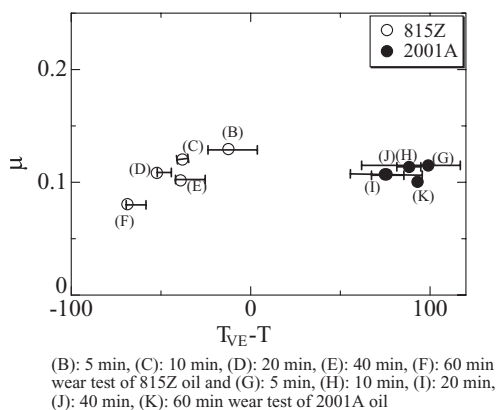


Fig. 10—Relation between friction coefficient μ and $T_{VE} - T$ (where T_{VE} is the viscoelastic solid transition temperature at pressure p , and T is the oil temperature. $T_{VE} - T < 0$; liquid, $T_{VE} - T > 0$; solid).

is closely related to the oil molecular packing parameter $T_{VE} - T$ similar to EHL condition (Ohno et al. (23)).

CONCLUSION

Summarizing the experimental results, the following conclusions are drawn concerning the friction and wear characteristics of advanced space lubricants under boundary lubrication at ground level.

1. The highest wear scar was found for base oil 815Z, but it showed the lowest coefficient of friction. Whereas greases 600EF, 601EF (containing rust and corrosion inhibitor), and 602EF (containing molybdenum disulfide) blended with base oil 815Z, base oil 2001A, and grease R2000 blended with base oil 2001A showed smaller wear scar and considerable friction coefficient.
2. This unique phenomenon of base oil 815Z was investigated from the phase diagram of base oil 815Z. The decomposition of base oil 815Z containing the acetal group ($-OCF_2O-$) occurred by mechanical shear at high shear rate in the elastic-plastic solid. Hydrogen fluoride is released with the decomposition of acetal group. As a result, the corrosive action of hydrogen fluoride increased the wear rate of the steel ball in the 815Z base oil.
3. The friction coefficient μ under boundary lubrication is closely related to the oil molecular packing parameter $T_{VE} - T$.

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