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Use of VHVI Base Oils for High Performance ATFs

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Abstract : Performance requirements for automatic transmission fluids have been changed reflecting the design changes of automatic transmissions. The major purpose of these design changes is concentrated upon improvements of both fuel economy and drivability. In order to formulate such high performance ATFs as satisfy those requirements, it is necessary to use high quality base oils like VHVI base oils and PAOs. In this study, the effect of base oils characteristics on ATF performance is investigated, mainly regarding differences in frictional characteristics with deterioration. Frictional characteristics are determined using the SAE No. 2 machine and ATFs are deteriorated under various controlled conditions. Moreover, low-temperature fluidity, oxidation stability, and seal compatibility are also compared for four different ATFs. From the investigation, it was found that the use of Group III and IV base oils in ATFs gives several benefits with respect to low temperature viscosity, oxidation stability and SAE No.2 friction characteristics.

Key words : Base oils, automatic transmission fluid, friction characteristics, deterioration, oxidation, SAE No.2, VHVI

Introduction

Recent trend in vehicle transmission designs has mainly been focused on energy saving and easy driving. Introduction of new designs and mechanisms simultaneously requires new high-performance lubricants for them, as they generally impose more severe conditions on lubricants.

Related to improvements in fuel efficiency of AT, requirements for ATFs have become stringent regarding anti-shudder and torque capacity. Moreover, low-temperature fluidity and frictional characteristics are also important for the sake of easy driving. In addition, requirements for maintenance-free transmissions necessitate ATFs of high performance which can function without trouble for a long period under the conditions of high temperature and high shear, etc.

Therefore, it has been required to improve oxidation stability, shear stability, friction durability and seal compatibility. In order to formulate the high performance ATFs which can satisfy the recent requirements, additive formulation technology is very important especially for friction control but should be well balanced and optimized with base oils technology. Now, the use of high-quality base oils in ATFs is well established to improve low-temperature fluidity and oxidation stability, etc.

The effect of base oils characteristics onATF performance is not fully understood, perhaps because the formulation of ATF is very complex and also different according to vehicle designs, operating conditions and properties of base oils and additives. Moreover, it is very difficult to separate factors influenced by base oils from the ones by additives as the deterioration process of ATF is very complicated during endurance performance tests. However, the following two factors are mainly related to the deterioration and performance of ATFs: 1) depletion of additives and 2) deterioration of base oils.

In this study, the effect of base oils characteristics on ATF performance is investigated, mainly regarding differences in frictional characteristics with deterioration. Frictional characteristics are determined using the SAE No. 2 machine and ATFs are deteriorated under various controlled conditions. Physico-chemical properties are determined for fresh and used ATFs and the surfaces of paper clutches are also analyzed after testing. Moreover, low-temperature fluidity, oxidation stability, and seal compatibility are also compared for four different ATFs.

ATFs and their Characteristics

ATFs are prepared with different base oils and their physico-chemical properties are determined. ATFs are deteriorated in both an oxidation bench tester and the SAE No. 2 machine. Changes in their properties during deterioration are followed up by sampling and analyzing the deteriorated oils. Deterioration in general oil performances is discussed in relation to the changes in the physico-chemical properties.

Preparation of lubricants

Physico-chemical properties of four fresh ATFs used in the experiments are summarized in Table 1.

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Table 1. Physico-chemical properties of four fresh ATFs used in the experiments

Properties	ATF-1	ATF-2	ATF-3	ATF-4	Specification	
					Dexron III	Mercon
Specific Gravity	0.8649	0.8605	0.8438	0.8309		
Kinematic Viscosity @40°C, cSt	37.65	36.73	33.42	29.41		
@100°C, cSt	7.670	7.647	7.382	6.836		Min. 6.8
Viscosity Index	179	184	196	204		
Brookfield Viscosity @-20°C,cP	1420	1570	1070	670	Max. 1,500	Max. 1,500
@-30°C,cP	5230	6140	2570	1520	Max. 5,000	
@-40°C,cP	26500	44250	9360	4150	Max. 20,000	Max. 20,000
Pour Point, °C	-47.5	-45.0	-52.5	<-52.5		
Aniline Point, °C °C	100.8	106.6	115.0	119.8		
TAN, mgKOH/g	0.78	←	←	←		

ATF-1, 2, 3 and 4 were blended at the same treat rate with an additive package which satisfies the requirements of GM Dexron III and Ford Mercon and is composed of anti-oxidant, anti-wear agent, dispersant, detergent and modifiers of friction and viscosity, etc. However, the base oils in them are different for each ATF. As shown in Table 2, various base oils, BO-1, 2, 3 and 4, are blended at the same treat rate for each ATF, respectively. All the base oils are 100 neutral grade with viscosity of about 4 cSt at 100°C but they are different in their quality and classified as Group I, II, III and IV, respectively, according to the recent API base oil classification. BO-1 and 2 are typical conventional base oils and BO-3 and 4 are a VHVI base oil and a PAO, respectively.

Low temperature fluidity and seal compatibility

Low-temperature fluidity is very important because high viscosity at low temperature could cause slow operation of transmission and poor startability of torque converter. As shown in Table 1, the low-temperature viscosities, determined at –20, –30, –40°C, are better with ATF-3 and 4 satisfying the requirements of Dexron III and Mercon. Figure 1 gives changes in low-temperature viscosities with decreasing temperature from –10 to –50°C, which were determined using a scanning Brookfield viscometer. The oil ATF-4 also gives the best low temperature fluidity, whileATF-3 is better thanATF-1 and 2.

Table 2. Properties of base oils

API Base Oil Group	I	II	III	IV
Properties	BO-1	BO-2	BO-3	BO-4
Specific Gravity	0.864	0.855	0.834	0.819
Kinematic Viscosity @ 40°C, cSt	20.08	20.20	19.57	17.10
@100°C, cSt	4.13	4.15	4.23	3.86
Viscosity Index	106	107	122	127
Flash Point, °C	220	214	218	224
Pour Point, °C	-10	-10	-15	-57
Sulfur, wt%	0.58	0.03	0.00	0.00
Aromatics by HPLC, vol%	27.7	3.5	0.6	0.0
Aniline Point, °C	100	105	113	115

Because various seal materials are used in the hydraulic systems of automatic transmissions, seal compatibility of ATF is important for proper operation. With respect to six seal materials which satisfy the specification of Dexron III, their

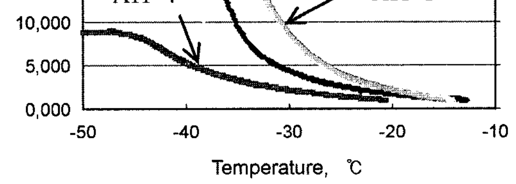


Fig. 1. Low-temperature viscosities with decreasing temperature from –10 to –50°C.

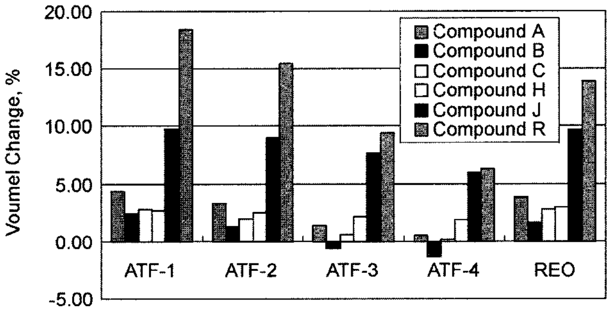


Fig. 2. Volume changes of various seal materials.

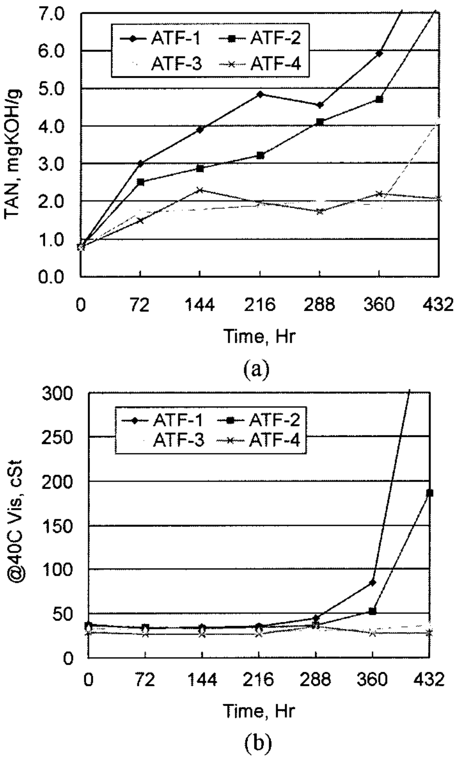
Table 3. Test conditions of beaker oxidation test

Item	BOT	ABOT
Temp.,	155	155
Catalyst	Cu/Fe Wire	Aluminum Beaker Cu/Al Strip
Air, L/Hr	10	0.3
Oil Volume, ml	400	250
Time, Hr	432	300

volume changes were determined after aging at 150°C for 70 hours. In Figure 2, their differences are compared among five oils including a reference oil REO, which satisfies the Dexron III specification. While the volume changes with ATF-1 and 2 are larger than or similar to the REO, the ones with ATF-3 and 4 are considerably less than ATF-3 and 4. These results indicate that minor reformulation of base oils and/or additives are necessary for ATF-3 and 4.

Oxidation stability

Among the performances required for ATF, the oxidation stability is very important as over 70% of automatic transmission failures were known to be related to fluid oxidation [1]. As ATF undergoes deterioration during service under the oxidative conditions, sludge and varnish can be deposited on the transmission parts and deteriorated materials can corrode bearings and bushings and also harden the various elastomeric seals. Recent design changes make the fluid temperature even higher and it has been reported that fluid life is primarily limited by oxidation during severe service [2].



(a)

(b)

Fig. 3. Deterioration during BOT: changes in (a) TAN and (b) viscosity.

Oxidation processes in transmission can be simulated by a Ford method, ABOT (Aluminum Beaker Oxidation Test), only if the test conditions are carefully controlled [3]. In order to evaluate oxidation stability, the test conditions, shown in Table 3, were selected, which are similar to ABOT method. During the deterioration process, we took samples and determined total acid number (TAN) and viscosity at 40°C.

As shown in Figure 3(a), TAN of ATF-1 and 2 increases steadily with increasing oxidation time but the increasing rate is higher with ATF-1 than with ATF-2. However, TAN of ATF-3 and 4 levels off at about 2 mg/KOH after 144 hours. This indicates that more oxidation products be generated with ATFs blended with conventional base oils, BO-1 and 2.

Viscosity at 40°C shows almost no changes until 288 hours for all the oils, as shown in Figure 3(b). After 360 hours, the viscosity increases rapidly with ATF-1 and 2 but stays unchanged with ATF 3 and 4.

Frictional Characteristics

Frictional characteristics of ATFs are investigated through friction tests which are conducted using SAE No. 2 machine with various lubricants, both fresh and deteriorated under different conditions.

Experimental

A general view of the SAE No. 2 machine is given in Figure 4 and testing conditions in Table 4 are compared with other standard methods. This machine is often used in specification tests including Dexron III and Mercon.

The present experiments are different in its severity which can be defined as follows [4]:

$$\text{Severity Index} = \frac{(\text{Energy per Cycle})\times(\text{Number of Cycles})\times(\text{Fluid Temperature})}{(\text{Net Surface Area})\times(\text{Fluid Volume})}$$

Figure 5 shows typical data taken from the machine, which include μs, μo, μd, $\mu o/\mu d$ and stop time. During a run of 10,000 cycles, the friction data are continuously determined and oil samples are periodically taken for analysis

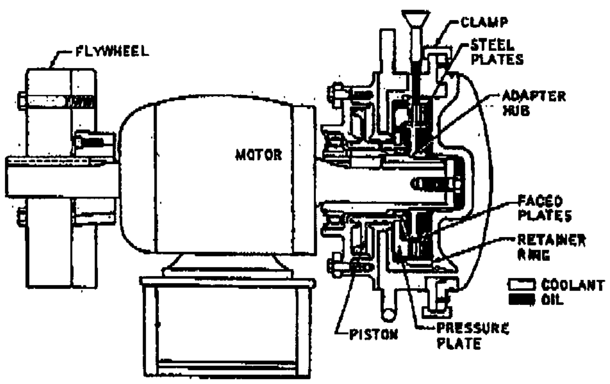


Fig. 4. General view of SAE No. 2 machine.

Table 4. Comparison of SAE No.2 test conditions

Item	Condition A	Condition B	GM Dexron III	Ford Mercon	JSAO
Friction Material	SD 1777X	←	SD 1777	SD 1777	SD 1777
Friction Material Size (o.d./i.d.), mm	127/104	←	125.4/90.5	133.4/98.8	126.5/105
Plate Arrangement (F=Friction Plate, S=Steel Plate)	S-F-S- S-F-S	←	S-F-S-S-F-S	S-F-S-S-F-S	S-F-S-F-S-F-S
Fluid Volume, L	0.30	←	0.65	0.30	0.60
Fluid Temperature, °C	120	140	140	115	100
Energy, J	16,909	←	15,700	20,740	24,350
Inertia, kgm2	0.343	←	-	-	0.343
Dynamic Test Speed, rpm	3,000	←	3,600	3,600	3,600
Static (Breakaway) Test Speed, rpm	0.7	←	0.72	4.37	0.72
Apply Pressure, kPa	441	←	345	275	785
Gross Friction Area, mm^2 (per surface)	4,171	←	5,920	6,310	3,910
Groove Type	grooved	←	none	grooved	none
Net Friction Area, mm2	13,228	←	23,680	16,384	23,460
Cycle Length, s	30	←	20	20	30
Test Cycle	10,000	←	18,000	15,000	5,000
Test Duration, h	83.3	←	100	83.3	41.7
Energy per Total Net Friction Area, J/mm^2	1.013	←	0.663	1.266	1.038
Energy per ATF Volume, J/L	56,400	←	24,200	69,100	40,600
Cumulative Energy Absorbed During Complete Test, kJ	169,090	←	282,600	311,100	121,750
Test Severity Index*	5.11	5.97	2.57	7.28	0.86
Catalyst(Metal Naphthenate)	-	Cu/Fe 40 ppm	-	-	-

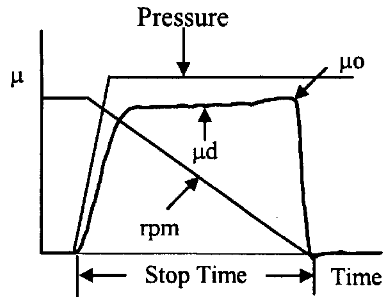
Effect of base oils and test conditions on friction characteristics

The variations of frictions μs and μd, the ratio $\mu o/\mu d$ and stop time with testing cycles are shown in Figure 6(a)-(d) for the experiments under the conditions A with four ATFs 1-4, respectively. The data of each friction, the ratio and stop time in the figures are drawn from the original records at every cycle.

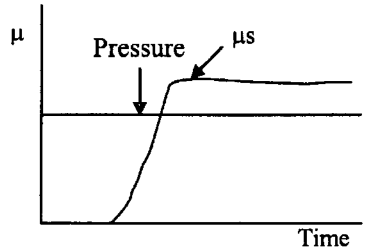
The static friction μs with ATF-4, Figure 6(a), shows considerable differences from other oils ATFs 1-3. The friction of all the oils ranges from 0.11 to 0.12 at the initial and early stages. Then the friction increases gradually and exceeds 0.12 for ATF 1-3 after runs of about 3,000 cycles, but for ATF-4 after 6,000cycles.

The dynamic friction μd stays at the same level for all the runs of 10,000 cycles and its behavior is basically the same for all the oils tested, as shown in Figure 6(b). Figure 6(c) shows the changes in the friction ratio $\mu o/\mu d$ with testing cycles. After slight decreasing at the initial stage, they increase slowly with cycles but stay at acceptable levels even at the end of the runs. The stop time also shows no considerable differences among the oils as shown in Figure 6(d).

As the testing temperature 120°C is too mild to deteriorate the base oils and additives in the ATFs, it is considered that deterioration of oils is very limited even after the runs of 10,000 cycles. In order to increase the severity of test conditions, we increased temperature to 140°C and added soluble iron and copper catalysts to the level of 40 ppm.

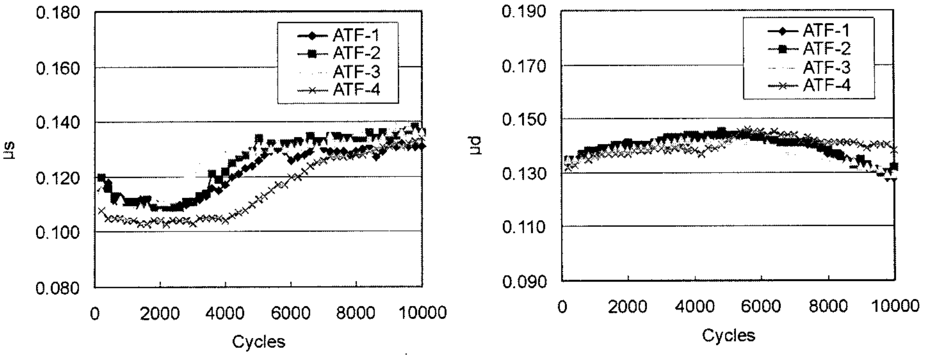


Dynamic Mode



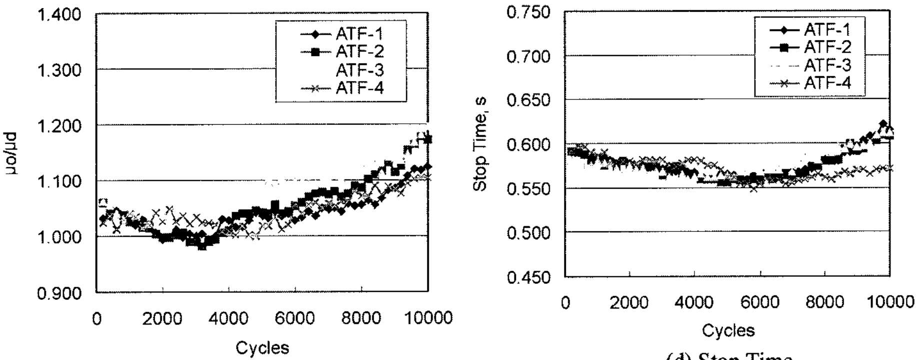
Static Mode

Fig. 5. Typical data taken from SAE.



(a) μ-Static

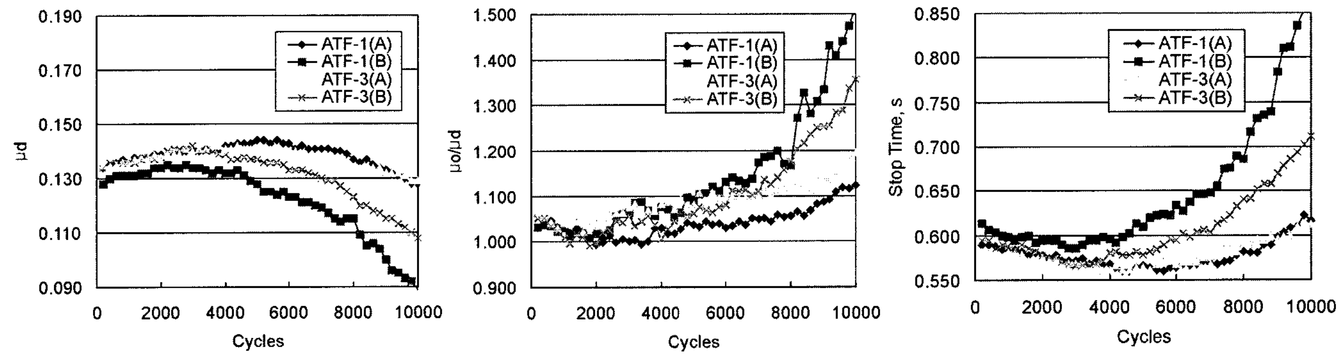
(b) μ-Dynamic



(c) μo/μd

(d) Stop Time

Fig. 6. Test results of SAE No. 2 by condition A.



(a) μ-Dynamic

(b) μo/μd

(c) Stop Time

Fig. 7. Test results of SAE No. 2 by condition A and B.

As no changes were observed in static friction μs even under the conditions B, dynamic friction μd, the friction ration $\mu o/\mu d$ and stop time are compared in Figure 7(a)-(c). With respect to all characteristics shown in Figure 7, big differences exist between ATF-1(A) and ATF-1(B), between ATF-3(A) and ATF-3(B) and between ATF-1(B) and ATF-3(B). After about 5,000 cycles, ATF-1(B) and ATF-3(B) start to increase rapidly with respect to all three parameters but the change are much higher with ATF-1(B). This indicates that conditions B are more stringent than conditions A. As shown in Figure 8, the increase in total acid number is higher after the testing under conditions B than A. This indicates that the increase of oxidation products in oils has correlation with deterioration of their friction characteristics.

Effect of oxidation on friction characteristics

Fresh ATFs 1-4 were deteriorated through BOT for 72 hours at the conditions described in Table 3. The deteriorated oils are designated as OATFs 1-4, of which total acid numbers were 3.0, 2.5, 1.7, 1.5 mg/KOH, respectively.

Figures 9(a)-(c) show the changes of μd, $\mu o/\mu d$ and stop time for OATFs 1-4. Clear differences in their changes also exist between OATF 1,2 and OATF 3,4.

At the early stages of the runs, the frictional characteristics are almost the same for all the oxidated oils, but the differences between the two groups grow bigger and bigger with increasing cycles. From the fact that in spite of their different degree of oxidation the friction is almost the same at the initial stages of the runs for all the oils, it is clear that deterioration of

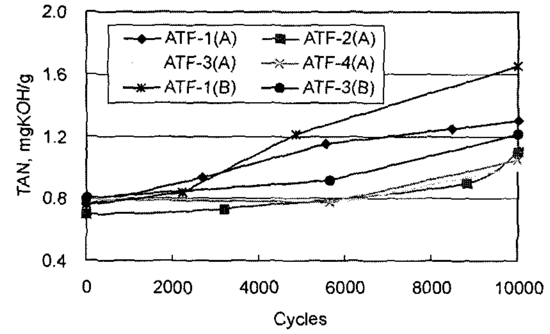


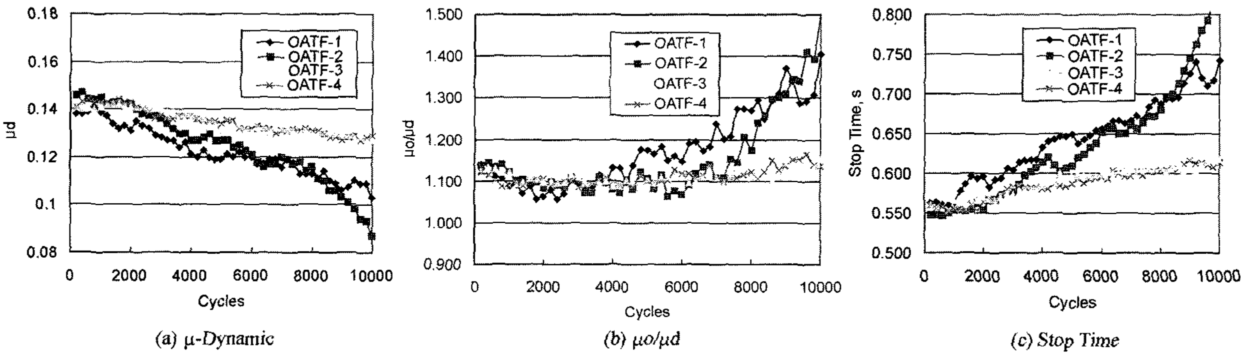
Fig. 8. Change of TAN during SAE No. 2 test.

friction materials with increasing cycles is more important than the frictional property itself of deteriorated ATFs.

When TAN was determined after the runs, it decreased from 3.0 to 1.9, from 2.5 to 0.9, from 1.7 to 0.8 and from 1.5 to 1.0 mgKOH/g for OATF 1-4, respectively. This fact means that some of the oxidation materials existing in the deteriorated oils have been consumed during the friction runs. From the fact that frictional parameters continuously become worse even though TAN of the oils decreases with increasing cycles, it is indicated that the oxidation materials not influence directly on the friction but indirectly. That is, they changes the properties of surface materials

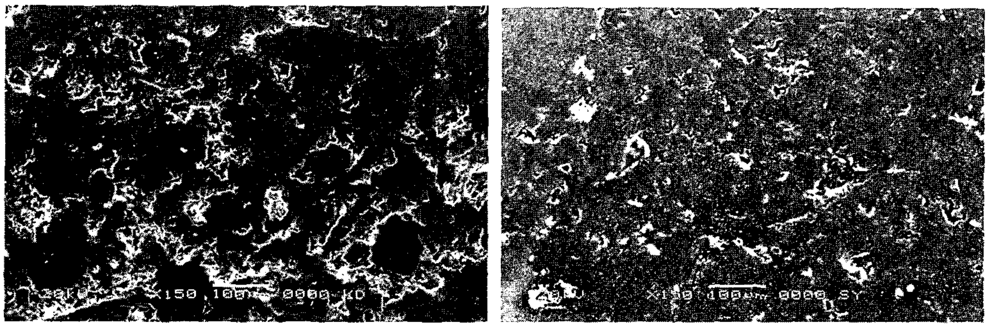
As SEM micrographs of friction plates after the tests are shown in Figure 10, it is found that the surface pores of friction plates are plugged with deteriorated materials when compared with the surface of new plate, Figure. 11. The degree of pore plugging of OATF-1,2 is more severe than OATF-3,4.

From the above fact, it is clear that oxidation products which were made during oxidation tests have consumed and deposited on friction plates during the runs. These phenomena resulted in difference of friction characteristics among OATF 1-4. We could also find additive metals from elemental

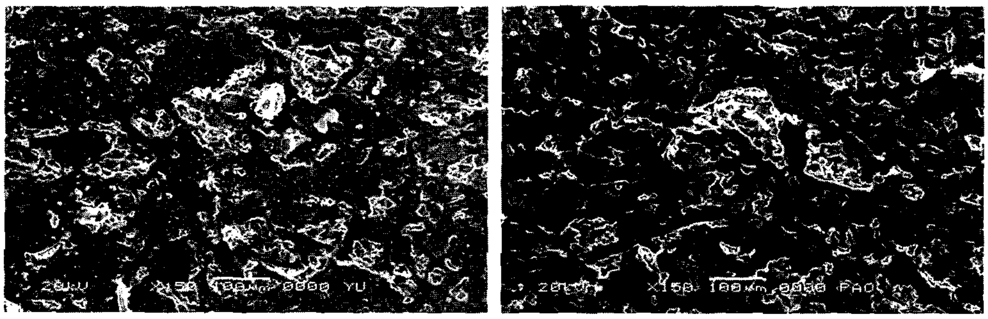


(a) μ-Dynamic (b) μo/μd (c) Stop Time

Fig. 9. Test results of SAE No. 2 of deteriorated ATFs by Condition A.



(a) OATF-1 (b) OATF-2



(c) OATF-3 (d) OATF-4

Fig. 10. SEM micrographs of friction plate after 10,000cycle of SAE No.2 test with the oxidated oils.

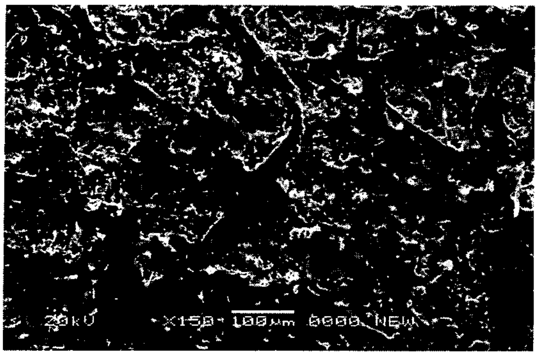


Fig. 11. SEM micrographs of new friction plate.

analysis of the deposited materials. It is also possible that oxidation materials accelerate both decomposition of additives and deterioration of surface materials to produce higher deposits on surface and to plug the pores. In order to improve the frictional performance of ATFs, it is important to reduce the plugging of surface pores by improving oxidation stability of base oils, additives and surface materials.

Conclusions

In this paper, in order to extend the understanding of the effect of base oils characteristics on ATF performance, low temperature viscosities, seal compatibility, oxidation stability and SAE No.2 test with several conditions were evaluated and following conclusions are obtained.

(1) Low temperature properties of ATFs within use of same additives are restricted by those of base oils
(2) Oxidation Stability of ATF-3 and 4 formulated with Group III and Group IV is better than that of ATF-1 and 2 formulated with Group I and II.
(3) In SAE No. 2 test, frictional characteristics are similar under mild conditions among base oils, but under severe conditions frictional characteristics significantly different between high quality base oils and conventional base oils.
(4) Frictional charateristics of ATFs are affected by the fiction plate plugged by oxidation products rather than oxidation products themselves.
(5) In order to improve the frictional performance of ATFs, it is important to reduce the plugging of surface pores by improving oxidation stability of base oils, additives and surface materials.

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