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WEAR AND SCUFFING CHARACTERISTICS OF POLYVINYLEETHER(PVE) IN AN HFC ATMOSPHERE

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ABSTRACT

Tribological characteristics of polyvinylethers(PVE), linear polyolesters(L-POE), branched polyolesters (HS-POE) and polyalkylene glycols(PAG) were studied using an HFC sealed block on ring wear tester. PVE and PAG showed lower wear and higher scuffing load capacity than L-POE and HS-POE. Due to the high viscosity-pressure coefficient of PVE, a strong oil film in the elastohydrodynamic lubrication(EHL) condition prevented a direct contact between the rubbing surfaces. Due to its high absorption ability, the POE’s formed an absorbent film. This film was not strong and easily broken down. This oil film breakdown resulted in micro-scuffing between the rubbing surfaces.

INTRODUCTION

Because of the ozone layer protection issue, the manufacturing of Chlorofluorocarbon (CFC) refrigerants has already come to an end. Additionally, phase-out dates have been implemented for the use of Hydrogenated Chlorofluorocarbons(HCFC). HCFCs will be almost totally eliminated by the year 2020. Because of mandated phase-out dates, HFC-134a was evaluated and accepted by the automotive industry as the replacement refrigerant for CFC-12 for a mobile air conditioning application. PAG was the primary refrigeration oil used in the automotive open-compressor application. Because of a low specific electric resistance, PAG could not be used with hermetic compressors in stationary air-conditioning equipment. Both Polyvinylether(PVE) and Polyolester(POE) have good specific electric resistance. They were chosen as the refrigeration oil in this application. Limited numbers of these AC systems have already been launched with these lubricants. Since long term reliability is a requirement for refrigerators and air conditioners, the lubricants must have good lubricity characteristics with the use of non-chlorinated refrigerants such as HFC-407C or HFC-410A. Wear and scuffing characteristics of PVE, POE and PAG in HFC atmospheres were studied in this report. The test conditions were decided by calculated results of the contact condition between a rotor and vane of an actual compressor. Furthermore, the lubrication mechanisms of these oils were studied under the elastohydrodynamic lubrication(EHL) and boundary area of lubrication conditions.

TEST PROCEDURE

Test Units and Test Conditions

An HFC-134a sealed block on ring tester was used to evaluate the wear and scuffing properties of the lubricants. The schematic of the testing apparatus is shown in Fig.1. Two kinds of material combinations were used for test pieces. The details of the test pieces are shown in table.1. The block on ring tester with oil was evacuated for five minutes by vacuum pump prior to the introduction of refrigerant. Then HFC-134a was introduced into the apparatus until 0.5MPa pressure was achieved. This procedure was repeated twice. As previously stated, the test conditions for Test-1 and Test-2 were based on the calculated results of the contact friction condition between a rotor and vane of an actual compressor as reported by Tanaka et al.40

Test-1: Wear/Short duration Test Conditions: Low sliding speed and high contact pressure condition. The
lubricating condition would shifted to the boundary region under this test condition. The anti-wear performances were evaluated by the wear weight loss (mg) of the ring. The wear weight loss of the blocks were very close to 0 mg.

Test-2: Scuffing Test Conditions: High sliding speed and step-up load conditions were selected. The scuffing load was monitored throughout the test. The scuffing load was decided by the sudden rise of the friction force.

Test-3: Aluminum Wear test conditions: The wear test were performed with aluminum rings and blocks. The anti-wear performance of the test oils were evaluated by the wear width of the block. All the test conditions are shown in table 2.

The oil film strength was also tested utilizing an electrically isolated 4-ball tester. The tests were performed in an R-134a bubbling (50ml/min) atmosphere. The oil film failure was determined by the measured electrical potential between the balls. The testing apparatus schematic is shown in Fig.2. The followings are the test conditions:

- Oil temperature: 50°C
- Ball: 3/4 inch, SUJ-2
- Revolution: 500rpm
- Electrical potential: 15mv
- Test load: 50N increased every 3 min.

The oil film strength was calculated by the following equation:

\[ \text{Electrical separation ratio} = \left( \frac{\text{measured voltage}}{\text{added voltage}} \right) \times 100 \]

Lubricants

PVE, PAG and POE (Linear type: L-POE and Branched type: HS-POE) were the test oils selected. All oils were miscible with HFC refrigerants. Viscosity grades #32 and #68 were selected for each type of oil. The properties of the oils are shown in table 3.

TEST RESULTS

Test#1: Anti-wear characteristics of oils:

The wear weight loss (mg) of the rings are shown in Fig.3 & 4. PVE and PAG test results showed less wear weight loss than did the L-POE and HS-POE at viscosity grades #32 and #68. In the wear case of the #68 grades, the weight loss of the L-POE was less than the wear weight loss of the HS-POE containing 400ppm phosphorous (TCP:0.5%).

Test result estimations with the POE's are as follows:

* TCP did not enhance the anti-wear performance of the POE
* L-POE had a higher viscosity than the HS-POE at the test temperature (100°C) due to having a high viscosity index.

The specific wear rate of the ring tested with PVE #32 was calculated at \( 6 \times 10^{-11} \text{mm}^3/\text{N} \). This wear amount suggests the test condition could simulate the wear under a boundary lubrication condition. Measurement of the friction surface roughness and microscopic observation of the test rings were performed before and after the test to study the wear mechanism. The results are shown in Fig.5. The following three items were confirmed from these results.

1. The friction surface tested with PVE was slightly broken and showed little change.
2. The friction surface tested with L-POE or HS-POE became rougher and many scratches were observed.
3. The friction surface tested with PAG, which has the same anti-wear level as PVE, was smooth.

Test#2: Anti-scuffing characteristics of oils:

The block on ring tester with test oil was evacuated and HFC-134a was introduced in the same procedure
as in test#1. To evaluate anti-scuffing characteristics of the tested oils, a high sliding speed condition was selected and the load was increased by 100N every 3 minutes for the duration of the test. Test results are shown in Fig.6. The anti-scuffing load capacity was as follows:

\[ \text{PAG} > \text{PVE} > \text{L-POE} > \text{HS-POE} \]

High anti-scuffing performances were observed with PAG and PVE. The results with HS-POE showed a poor anti-scuffing performance. We consider the reasons for the high anti-scuffing performance of the PAG are as follows:

* PAG had a high viscosity at the test temperature (100°C).
* The friction surface tested with PAG easily remained smooth, as observed in Test#1.

Test#3: Anti-wear characteristics of oils with aluminum:

The anti-wear tests with aluminum were performed under the conditions shown in Table-2. The test results are shown in Fig.7 and 8. The viscosity grades tested were #32 and #68. The anti-wear performances of both grades of oils are as follows:

<table>
<thead>
<tr>
<th>Grade</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>#32</td>
<td>PVE &lt; PAG &lt; POE</td>
</tr>
<tr>
<td>#68</td>
<td>(good)</td>
</tr>
</tbody>
</table>

The HS-POE and L-POE did not show good lubrication effect with aluminum. An additional anti-wear test was performed with PVE and HS-POE in an air atmosphere. The HS-POE showed poor anti-wear performance in this environment as well. The test results are shown in Fig.9. When using POE with aluminum, proper counter measures must be considered in material quality selection and lubricant additives.

Oil Film Strength:

To study the anti-wear characteristics of PVE, POE and PAG from the point of oil film strength, a Modified 4-Ball Testing apparatus was utilized. The electrical potential between the rotating ball and fixed balls was observed under an HFC-134a bubbling atmosphere. The test results are shown in Fig.10. L-POE could not maintain an electrically isolated oil film at a vertical load of 50N (P<sub>max</sub>: 1.75GPa). HS-POE is better than L-POE, but still not as good as PVE or PAG. By these results, we cannot expect the POE's to form a strong oil film between the friction surfaces. The oil film strength of PAG and PVE were measured as high as 130N (2.45GPa) and 150N (2.56GPa) respectively. This phenomenon would suggest that the PVE and PAG have the ability to form a strong oil film.

DISCUSSION

The study of wear and scuffing characteristics of four refrigeration oils with different molecular structure and properties were evaluated. The molecular structures of the tested oils can be seen in Fig.11. PVE and POE oils have different anti-wear characteristics. We attempted to analyze the relationship between oil film strength and anti-wear performance. The following items needed to be effective to reduce the wear of the rubbing surfaces in the boundary lubrication region.

* Strong oil film formation to prevent metal to metal contact of the rubbing surfaces.
* Prevent abrasive and corrosive wear in the boundary lubrication region.

The microscopic photographs shown in Fig.5 depict the micro scuffing apparent on the friction surface tested with HS-POE and L-POE lubricants. The photographs also show that there were very few scratches on the friction surface tested with PVE. Furthermore, the POE showed lower oil film strength than the PVE when tested with a modified 4-ball tester.

These facts explain that the POE can not form a strong enough oil film to prevent scuffing in the boundary lubrication region. POE showed a low scuffing load capacity in Test#2. We assume the reason this occurs is that under a high sliding speed, where frictional heat is generated, micro scuffing occurred on the rubbing
surfaces. This easily and quickly developed into total scuffing. PVE has a high viscosity-pressure coefficient ($\alpha$). This characteristic enables the viscosity of the PVE to remain high enough in the EHL condition to protect the rubbing surface from wear and scuffing with a thick oil film. Under the EHL condition, the solidified oil film provided by the PVE has a high resistance to breakdown under shear stress as reported Kim et al. From these facts, the lubricating mechanism of these oils are explained as follows:

* PVE can form a strong oil film under the EHL condition and protect the rubbing surface from wear and scuffing by a strong solidified oil film.
* The oil film formed by POE is not strong and easily breaks down. The micro scratching that occurred on the rubbing surface resulted in wear under a low sliding speed condition. And resulted in scuffing under a high-speed condition.

It was reported that POE produced carboxylic compounds under the same severe boundary lubrication condition. The carboxylic compounds were produced by the POE's reaction with iron. This reaction occurs due to the $\text{C}=\text{O}$ bond present in the POE. The carboxylic compounds formed on the friction surface. These compounds do not have good lubricating properties due to their short carbon-chain structure. These compounds are easily removed from the friction surface by rubbing. The molecular bonds of PVE consist of $\text{C}-\text{C}$, $\text{C}=\text{O}$, $\text{C}=\text{O}$. Because there is no $\text{C}=\text{O}$ bond in PVE, there were no carboxylic compounds produced. This phenomenon explains why POE showed significant wear in the testing. We assume these factors were totaled and resulted in the significant wear differences between PVE and POE.

CONCLUSION

Wear and scuffing characteristics of PVE, POE and PAG were studied in an R-134a atmosphere. The following results were revealed:

1. PVE and PAG showed better anti-wear performance than POE(HS-POE/L-POE) under a boundary lubrication condition. PVE has the ability to form a thick oil film in the EHL region. This oil film had a high resistance to breakdown under shear stress. On the contrary, POE could not form a strong oil film and the result was micro-scratches on the friction surface. The authors suggest that this micro scuffing occurred and developed into serious wear during the duration of the testing period.

2. PVE and PAG showed a higher anti-scuffing ability than did the POE. Under a high sliding speed condition with POE, the micro-scratches quickly developed and caused a scuffing condition. This was due to the frictional heat generated by the high sliding speed test condition.

3. POE caused excessive wear for aluminum. Sufficient investigation is necessary concerning the quality of aluminum materials and oils being considered if aluminum is selected as a tribological material.

ACKNOWLEDGEMENT

The authors would like to acknowledge Prof. OHNO for providing viscosity-pressure coefficient data of test oils.

REFERENCES

### Table 1: Specifications of test materials

<table>
<thead>
<tr>
<th>Test</th>
<th>Block/Ring</th>
<th>Material</th>
<th>Hardness</th>
<th>Surface finish</th>
<th>Width</th>
<th>Ring diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test-1</td>
<td>Block</td>
<td>SKH-51</td>
<td>HRc50</td>
<td>Grinding (Rz 2.0 μm)</td>
<td>6 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35 mm</td>
</tr>
<tr>
<td>Test-2</td>
<td>Block/Ring</td>
<td>Eutectic graphite cast iron</td>
<td>HRc50</td>
<td>Grinding (Rz 1.6 μm)</td>
<td>6 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35 mm</td>
</tr>
<tr>
<td>Test-3</td>
<td>Block/Ring</td>
<td>Aluminum (A-4032 Si:12%)</td>
<td></td>
<td></td>
<td>6 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35 mm</td>
</tr>
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### Table 2: Test conditions

<table>
<thead>
<tr>
<th>Test</th>
<th>Load</th>
<th>Sliding speed</th>
<th>Oil temp.</th>
<th>Test duration</th>
<th>Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test-1</td>
<td>1200N</td>
<td>0.4 m/sec</td>
<td>100°C</td>
<td>120 min</td>
<td>HFC-134a(0.5 Mpa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test-2</td>
<td></td>
<td>Sliding speed</td>
<td>2.0 m/sec</td>
<td>Initial 100N</td>
<td>HFC-134a(0.5 Mpa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Added 100N in every 3 min.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test-3</td>
<td></td>
<td>Sliding speed</td>
<td>0.6 m/sec</td>
<td>Oil temp. 50°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Test duration 20 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Atmosphere HFC-134a(0.5 Mpa)</td>
<td></td>
</tr>
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</table>

### Table 3: Properties of test oils

<table>
<thead>
<tr>
<th></th>
<th>PVE32</th>
<th>L-POE32</th>
<th>HS-POE32</th>
<th>PAG32</th>
<th>PVE38</th>
<th>L-POE38</th>
<th>HS-POE38</th>
<th>PAG68</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (mm²/sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 40°C</td>
<td>33.94</td>
<td>24.52</td>
<td>30.33</td>
<td>32.27</td>
<td>72.09</td>
<td>65.94</td>
<td>70.14</td>
<td>43.94</td>
</tr>
<tr>
<td>@ 100°C</td>
<td>5.24</td>
<td>5.07</td>
<td>5.12</td>
<td>7.58</td>
<td>8.38</td>
<td>12.31</td>
<td>8.49</td>
<td>9.63</td>
</tr>
<tr>
<td>Viscosity index</td>
<td>77</td>
<td>139</td>
<td>96</td>
<td>216</td>
<td>82</td>
<td>186</td>
<td>89</td>
<td>212</td>
</tr>
<tr>
<td>Density (g/cm³, 15°C)</td>
<td>0.924</td>
<td>0.933</td>
<td>0.974</td>
<td>0.991</td>
<td>0.937</td>
<td>0.927</td>
<td>0.960</td>
<td>0.995</td>
</tr>
<tr>
<td>Viscosity-pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient: α</td>
<td>15.7</td>
<td>10.6</td>
<td>12.5</td>
<td>11.3</td>
<td>15.1</td>
<td>10.3</td>
<td>17.8</td>
<td>13.2</td>
</tr>
<tr>
<td>(GPa, @40°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric resistivity</td>
<td>1×10¹⁴</td>
<td>5×10¹³</td>
<td>5×10¹³</td>
<td>1×10⁹</td>
<td>1×10¹⁴</td>
<td>5×10¹³</td>
<td>5×10¹³</td>
<td>1×10⁹</td>
</tr>
<tr>
<td>(Ω-cm) @RT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorous (ppm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>0</td>
</tr>
</tbody>
</table>

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Fig. 1: HFC-134a sealed block on ring tester

Fig. 2: Electrically isolated 4-ball tester
Fig. 3 Wear weight loss of test rings (#32 grade)

Fig. 4 Wear weight loss of test rings (#68 grade)

Fig. 5 Microscopic photographs and roughness charts of friction surface

Fig. 6 Results of scuffed load

Fig. 7 Wear width of aluminum test blocks (#32 grade)

Fig. 8 Wear width of aluminum test blocks (#68 grade)

Fig. 9 Wear width of aluminum blocks (R134a and air atmosphere)

Fig. 10 Load and separation ratio

Fig. 11 Molecular structure of oils

(electrically isolated 4-ball tester)