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Test method

Effect of test parameters on degradation of polyurethane elastomer for accelerated life testing

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The degradation characteristics of polyurethane (PU) elastomer sliding against stainless steel were investigated using a pin-on-plate reciprocating tribo-tester in terms of the decrease in height of the specimen. From tests lasting for 234 h, which corresponded to a 270 km sliding distance, it was found that the rate of height decrease of the PU specimen ranged from 0.15 μm/km to 0.9 μm/km, mainly caused by compression set and wear. The height decrease rate of the PU specimen increased by a factor of 6 with increasing normal force and temperature while the general degradation characteristics were maintained. It was also shown that the use of discolored lubricant from service further increased the degradation of the PU specimen. Furthermore, signs of abrasive and adhesive wear of the PU elastomer were observed. The results of this work may provide a basis for designing an accelerated life testing method for hydraulic reciprocating seals.

1. Introduction

Hydraulic reciprocating seals are widely used to prevent fluid leakage in hydraulic systems of various industrial, automobile and aerospace applications. They are also designed to provide a lubrication film on counter elements to minimize friction and wear during operation [1]. The failure of a hydraulic reciprocating seal may lead to fluid leakage and, consequently, to the catastrophic failure of the hydraulic system. To mitigate such a failure, the hydraulic reciprocating seal is usually replaced in a timely manner. However, replacements require downtime of the hydraulic system and incur cost. To minimize such time and financial cost, the seal should have high reliability, and a good prediction of the life of the seal is highly desirable in order to be able to replace it at the appropriate time.

To predict the life of a machine element, accelerated life testing (ALT) is often employed since it is time-consuming and costly to obtain the necessary data from the field [2–4]. For ALT of hydraulic reciprocating seals, the main parameter that stimulates leakage failure is selected, and then controlled to accelerate the failure. However, ALT of hydraulic reciprocating seals often takes up to a few months to cause such a failure. Knowing this, the industry has sought ways to reduce the test time and cost. Therefore, the acceleration of the test parameter should be investigated and optimized to reduce the test time and cost.

To conform with the contacting surface, polymeric materials such as rubber, polytetrafluoroethylene and polyurethane (PU) elastomer are widely used as hydraulic reciprocating seal materials. Their viscoelastic properties affect the pressure distribution between the seal and the counter element and, consequently, the separation during operation, which influences the performance of the seal [5]. As for the failure mechanisms of hydraulic reciprocating seals, compression set, swelling, thermal deterioration and

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wear have been proposed [6–8]. In particular, the hydraulic reciprocating seal is readily worn during contact sliding, which increases the separation between the seal and the counter element. Thus, to extend the life of the hydraulic reciprocating seals, their tribological properties should be examined.

In the case of ALT for tribological systems, control parameters should be selected based on the wear mechanisms of actual operation, which may be adhesive, abrasive, fatigue or corrosive wear [9]. Then, the level of the parameter should be increased or decreased to accelerate such wear. For example, when abrasion is the main wear mechanism, adding suitable particles in the lubricant may accelerate the abrasive wear [10,11]. However, ALT often has difficulty reproducing wear that simply takes too long to occur (e.g. corrosive wear) or occurs due to the particles encountered in actual operation (e.g. erosive wear) [2]. Furthermore, in many tribological systems, more than one wear mechanism may be involved. In this case, a feasible ALT method would be to degrade the lubrication state. For example, in tribological systems where lubrication states vary from boundary to hydrodynamic lubrication, wear is expected to be more significant under boundary lubrication than under hydrodynamic lubrication [9]. Thus, a test with a low constant speed for boundary lubrication may accelerate wear [12]. Also, at a given total sliding distance, the sliding distance under boundary lubrication can be increased to accelerate wear [13]. To design a reliable ALT method like this, data should be accumulated from tests conducted under a wide variety of test conditions.

In this work, to improve the design of the ALT method with appropriate test conditions for the hydraulic reciprocating seal, the degradation characteristics of PU elastomer sliding against stainless steel (SS) were systematically investigated using a pin-on-plate reciprocating tribo-tester. Test conditions were selected with consideration of the typical operating conditions of the hydraulic system, so that the test can reproduce the degradation characteristics of PU elastomer in the hydraulic system. The degree of degradation was characterized by comparing the height of the specimen before and after the test. Then, the acceleration effects of the test conditions were identified based on the height decrease rate. The wear characteristics of PU elastomer were also considered after observing the sealing surface of the specimen.

2. Experimental details

2.1. Specimens

PU elastomer was selected due to its wide use as material for hydraulic reciprocating seals in industry. PU specimens were obtained from a commercial PU ring for conformal contact with the counter surface during the tests. Fig. 1(a) shows photographs of a PU specimen with the “U” cross-section. The width and length of the sealing surface of the PU specimen were about 2.4 mm and 8.6 mm, respectively. The elastic modulus and the hardness of the PU specimen were, respectively, 12 MPa and 94 (Durometer A). The average surface roughness of the sealing surface of the PU specimen, determined from confocal microscopy data, was 2.4 ± 0.4 μm (mean ± 1 standard deviation) before the test.

Chromium electroplated SS, widely used as material for cylinder rods in hydraulic systems, was chosen as the material for the counter surface. The SS specimen was cut from a cylindrical rod with a diameter of 50 mm to a length of 240 mm, as shown in Fig. 1(b). The hardness of the SS specimen measured by a Vickers hardness tester at five different locations was 680 ± 5 HV. The surface roughness of the SS specimen was determined to be 1.1 ± 0.1 μm from confocal microscope data obtained at five different locations. Since the hardness of the SS is much larger than that of PU elastomer, the wear of the SS specimen may be neglected [14]. Also, the mass transfer of PU to the SS surface can be suppressed by lubricant [15], and, therefore, surface contamination or damage of the SS specimen is not expected be a significant concern during the test.

The lubricant ISO VG 46, which is widely used in hydraulic systems, was used for the tests. Furthermore, to investigate the effect of degraded lubricant on the degradation of the PU specimen, the lubricants obtained from the field were used. Fig. 1(c) shows the photographs of the lubricants used in this work. Lubricant A is new while lubricants B and C are, respectively, lubricants obtained after 3,000 h and 1,000 h of operation in the field. The degree of discoloration of lubricant B was greater than that of lubricant C, probably due to severe operating and environmental conditions in the field. The viscosities of all the lubricants are in good agreement and are similar to that of ISO VG 46, as shown in Fig. 2(a). Also, the optical microscopy images of the particles separated from lubricants B and C by a rotary particle depositor are shown in Figs. 2(a) and (b), respectively. These clearly show that more particles are present in lubricant C than in lubricant B, which may be responsible for the greater discoloration.

2.2. Experimental setup and conditions

A pin-on-plate reciprocating tribo-tester was used in this work, as shown in Fig. 3. The PU specimen was mounted on the specimen holder and used as a pin. The PU specimen was slid against the SS mounted on a plate reciprocated back and forth by the motor. The stroke was set at 160 mm, and, therefore, the sliding distance of the PU specimen during one cycle was 320 mm. The sliding distance was set to about 270 km, which corresponded to about 234 h for each test. The normal force applied by a dead weight ranged from 98 to 196 N. These normal forces correspond to pressures from 4.7 to 11.7 MPa, which are within the typical range of the pressure on the hydraulic reciprocating seals during operation. The friction force was measured in real time to monitor the states of contact sliding during the tests. The heater was located below the SS specimen holder and the temperatures were set to 50, 80, 100, and 120 °C by considering the typical temperature range of the hydraulic fluid during operation.

In addition to the normal force and viscosity of fluid, sliding speed is one of the critical factors that influences lubrication state [16]. The lubrication state of the hydraulic reciprocating seal may vary from boundary lubrication to mixed lubrication or even to elastohydrodynamic