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Test method

Experimental method for wear assessment of sealing elastomers

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ABSTRACT

Elastomeric dynamic seals are components to prevent or to limit lubricant leakage in machinery. Nevertheless, they wear away under certain working conditions. Mostly, wear exists by starvation of lubricant film (two-body abrasion) and interaction with hard debris (three-body abrasion). This work aims to propose a suitable test methodology toward determining two-body and three-body abrasive wear rates of elastomers by using a TE66 Micro-Scale Abrasion Tester. In the tests, sections of silicone rubber were used. The experiments were divided in two parts. Firstly, dry runs were carried out replicating the two–body abrasion mechanism. Secondly, trials were run using two different media (contaminated oil and slurry) to reproduce three-body abrasive wear. Large viscoelastic deformations were generated in the samples and then they were considered for the wear estimation. In conclusion, the method shows advantages which make it suitable as an alternative test to obtain the wear behavior of sealing elastomers.

1. Introduction

Elastomers are extensively used to manufacture static and dynamic seals in machinery. They have many advantages, such as: High elasticity (good compliance with the contacting shafts), moderate creep and stress relaxation, relatively good resistance to abrasion, impermeability and chemical resistance to different media [1]. Their function is based on preventing leakages, while an elasto-hydrodynamic oil film is formed between the lip and the shaft which promotes an extended life of the seal [2]. However, in prolonged sliding contacts, dynamic seals fail due to abrasion and compression set being the most recurrent failures [3,4]. The wear is mainly produced either by partial dry running (lubricant starvation), or by interaction with abrasive hard fine particles (debris) [3]. Thus, the wear can be divided in two types: two-body abrasion and three-body abrasion. In the same way, Zhang classified the abrasive wear of rubber in two categories: dry abrasion and wet abrasion. For dry abrasion, it is basically produced by a rough and hard surface sliding against an elastomer surface under dry conditions. Typically, the wear patterns are series of periodic parallel ridges perpendicular to the sliding direction (tearing). Tearing is the common wear mechanism occurring in elastomers. It consists of a corrugated surface appearance formed by microdelaminations which are perpendicularly orientated to the sliding direction, resulting from micromolecular fracture or repeated rupture of molecular chains under continuous action of mechanical stresses [5]. On the other hand, wet abrasion was sub classified in two categories. One is wet abrasion acted by free particles that produce a local irregular micro-tearing process with micro-layered surface, while the other is action by fixed particles which generates a general micro-layering texture [5,6]. These experiments were carried out by a rubber pin-on-steel plate test.

In practice, the result of worn seals is the opening of gaps producing leakage. To prevent such a failure, the seal should be replaced in a timely manner, but precipitous replacement is undesirable since it interrupts the operation of machinery generating financial loss [4]. Hence, more suitable wear test methods are needed to predict the life of seals. There are some standard tests to determine the abrasion resistance of rubbers, such as: ISO 4649, ISO 23794, ISO 5470, ASTM D4060, ASTM D2228, and ASTM D5963. However, they only focused on characterizing two-body abrasion under extreme dry conditions. Many investigations of dry abrasion of elastomers have been carried out using the standard methods

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[6–12]. Furthermore, in order to approach the realistic working situation of dynamic seals, various experimental test methods have been developed. The works include the approximation of two-body abrasion under dry and wet/lubricated conditions, and three-body abrasion using a mixture of lubricant with hard debris [2,4,5,13,14]. Nonetheless, by contrast to the standard methods, these tests involve extremely long runs due to the lubricated contacts. Hence, an accurate and accelerated test method is needed to evaluate wear of sealing elastomers whilst saving time and reducing testing costs.

In previous research, three-body abrasion of elastomers has been tested by using a modified method to approach three-body abrasion patterns in micro-scale [15,16]. It was achieved by a modified experimental method which was developed to test hard materials [17–19]. Fundamentally, the original test is to initiate very small wear depths and volumes on the samples by a rotating ball covered with fine abrasive particles [20]. The wear scar formed on "small specimens" is a spherical cap which allows accurate determination of wear volumes. On the other hand, the wear crater obtained in elastomeric materials did not meet the spherical cap geometry since the high elastic deformations produced by the ball contact were recovered when the tests were ended [15,16]. The paper aims to provide a wear accelerated test method which replicates separately two-body and three-body abrasion of silicone rubber under dry, muddy and oily contacts to determine the wear behavior.

2. Experimental

2.1. Test specimens

The specimens were extracted from a commercial silicone rubber flat sheet (2 mm thick). The samples were small square pieces (10 × 10 mm). The specimens were characterized by using FT-IR analysis to obtain the chemical composition. This was realized using an ATR (objective 36X) from a module FT-IR (IR2) coupled to a spectrometer micro Raman LabRam HR800. Spectral data between 400 and 4000 cm^{-1} were collected averaging 32 scans at a resolution of 4 cm^{-1}. The FT-IR spectrum is illustrated in Fig. 1. There can be seen the characteristic peaks from a silicone rubber (poly(dimethylsiloxane)) [21,22]. The intense peaks identified corresponded to $Si–CH_3$ bonds at 1400 and 1260 cm^{-1}, together with CH_3 peaks near 2900 and 2950 cm^{-1}. Two Si–O peaks were also measured in the range of 1000–1100 cm^{-1}.

Steel balls (AISI 52100) of 25.4 mm diameter were used as sliding counterface after etching in 20% Nital solution for 20s, such that a fine pitting surface with a uniform roughness of 0.3 μm Ra was achieved, as suggested by Rutherford and Hutchings [17,18]. The roughness corresponds to the roughness value used in actual rotary shafts [23]. The roughness of the elastomeric samples was measured by using an optical profilometer (Contour GT-K, Bruker) while the roughness of the spheres was obtained by using a Dektak 150 stylus (contact) profilometer.

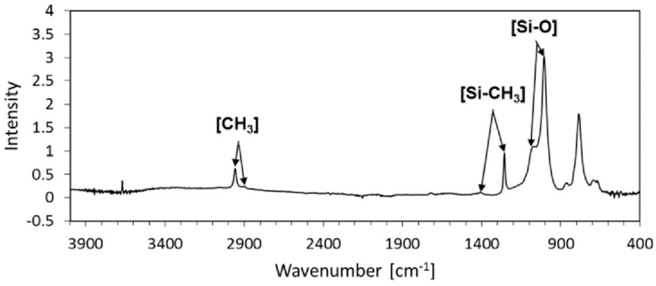

Fig. 1. FT-IR spectrum from the Silicone rubber specimens used for the testing.

The mechanical properties of the elastomeric samples and rotary spheres are shown in Table 1. The mean Poisson's ratio of silicone was estimated by a measuring technique based on digital image correlation which is explained later. Additionally, in order to estimate the approximated elastic modulus of the silicone samples, instrumented Berkovitch nano-indentation tests (CSM Instruments, TTX-NHT) were conducted. They were performed at room temperature (22 ± 2 °C). The indenter was kept in position at a maximum load of 5 mN for 10 s, and the loading rate was selected as 30 mN/min. In total, 5 indentations were performed for each sample.

2.2. Experimental set-up

The wear tests were carried out by using a TE66 Micro-Scale Abrasion Tester. A schematic illustration of the apparatus is shown in Fig. 2. The set-up consists of setting a sample vertically on a pivoted L-shaped arm and loading it against a rotating sphere with a selected normal force. The load is applied to the arm through a dead weight located on a horizontal lever. The counterbalance is used to balance the arm without weight before the test. The rotary ball is clamped between two coaxial driving shafts and rotated by a motor at constant speed. The sliding speed and revolutions of the sphere are controlled during the entire test. The oil and slurry are continuously jetted on top of the ball and entrained into the contact interface by the rotary effect.

2.3. Test procedure

Tests replicated the wear generated by dry running and by the presence of hard fine particles, two-body abrasion and three-body abrasion were simulated separately. The test conditions employed are shown in Table 2. On the one hand, tests were run under dry conditions. In this case, only the steel surface roughness has influence on wear (two-body abrasion). On the other hand, tests of three-body abrasion were conducted with silicon carbide microparticles (grade C5, F1200, approximately 4 μm particle size with angular morphology), see Fig. 3. Firstly, an oil mixed with SiC was used to replicate the actual lubricated contact of the sealing interface. However, consistent three-body abrasive wear scars were obtained under certain oily test conditions in previous work, in low sliding speed with high abrasive concentration [15]. A synthetic engine oil (5W-30) was used; its viscosity was 62.6 cSt at 40 °C and 10.7 cSt at 100 °C while the density was 0.856 at 15 °C. Secondly, the samples were tried in a muddy condition meeting the original method and to achieve three-body abrasion [17–19]. The slurry was made with distilled water and SiC particles. The contaminated oil and the slurry were continuously agitated throughout each test and constantly applied. The oil was jetted with a flow of 0.016 ml s^{-1} while the slurry was applied with a flow of 0.5 ml for each 10 sphere revolutions. The load was selected in order to reach an approximate contact pressure of 1.0 MPa, which is estimated as the actual contact pressure in dynamic seals [1]. The contact pressure was calculated by considering elastic contact between a ball on flat (Hertzian theory) [24]. Before the sphere started rotating, relaxation times of 1 h (for dry and muddy conditions) and 10 min (for oily contact) were spent after the ball made contact with the elastomeric sample. Three tests were performed for each experiment to indicate repeatability.

3. Results and discussion

3.1. Characteristics of the wear scars

The wear scars were studied in detail taking images of wear