Frictional behaviour of some sealing elastomers in lubricated sliding conditions

M. Mofidi¹*, B. Prakash²

1: Department of Mechanical Engineering, Sirjan University of Technology, Sirjan, Iran
2: Division of Machine Elements, Luleå University of Technology, Luleå SE-971 87 Sweden

Abstract
Frictional behaviour of four sealing elastomers, including an acrylonitrile butadiene rubber (NBR), a hydrogenated acrylonitrile butadiene rubber (HNBR), an acrylate rubber (ACM) and a fluoroelastomer (FKM), sliding against a steel surface under unidirectional lubricated conditions have been studied. The lubricant used in this study was paraffinic oil with no additive and the experiments were conducted under a block-on-ring test configuration. The friction coefficients of the elastomers have been measured at different sliding velocities in boundary and fluid film lubrication regimes. In the first part of each test, the sliding velocity varied from low to high values and then, in the second part, the sliding velocity varied from high to low values repeating the same conditions in reverse order. The results show that the friction coefficients at low speeds are different for the two parts which can be due to the oil absorption or possibly dissolution of some elastomer constituents in the oil. The NBR and the ACM were the least and the most affected elastomer by the lubricant respectively. The friction coefficients of NBR and ACM at low speeds decreased in the second part of the tests (in which the interaction of oil and elastomer was for longer durations) but the friction coefficient of HNBR and FKM increased in the second part of the tests.

Keywords: Elastomer, Friction, Lubrication

Corresponding author: Mohammadreza Mofidi (mofidi@sirjantech.ac.ir)

1. INTRODUCTION
The frictional behaviour of elastomers sliding against hard counterfaces in lubrication condition is of a great interest in sealing application. This behaviour is very complicated due to the influences of many factors including the elastomer and hard counterface properties, lubricant properties, contact geometry and elastomer-oil interaction. The friction coefficient of an elastomer sliding against a hard counterface can be expressed in terms of the contribution of adhesive, hysteretic (deformation), viscous and cohesive (tearing) components [1, 2]. However, most authors consider only two terms for friction components. They suggest that the tearing and viscous components can be represented by deformation and adhesive components respectively [1]. Adhesive component of friction originates from making and breaking of junctions at a molecular level [3]. Hysteretic friction is a consequence of energy loss associated with internal damping within the viscoelastic body [4]. The cohesive component of friction is the contribution of wear to the bulk losses and the viscous component is the viscous drag under lubricated conditions [1]. Since the contribution of the tearing component is significant when severe wear occurs, it is of less interest in real applications. The contribution of adhesion and hysteresis to friction depends on the geometry, cleanliness of the mating surfaces and contact pressure. In many applications, especially in lubricated conditions, the hysteretic friction is the dominant component. Even if the hard surface appears smooth to the naked eye, it may exhibit short wavelength roughness, which may make the dominant contribution to rubber friction in lubricated condition [5]. The adhesive component is dominant on very clean and smooth surfaces [6-9]. It can also be significant at low loads, even in lubricated conditions [10] because of the significance of the attractive Van der Waals’ forces between the surfaces compared to the normal load [11]. Presence of fluid between rubber and hard substrate reduces not only the adhesion but also the hysteretic components of friction. The lubrication decreases the real contact area between the rubber and hard counterface resulting in a decrease in friction coefficient. This effect is more pronounced at higher velocities due to hydrodynamic effects. On a lubricated surface, the valleys turn into fluid pools which are sealed off and thus make the surface smooth. This smoothening reduces the
viscoelastic deformation caused by the hard surface asperities, and reduces rubber friction [12, 13].

In elastomer lubrication the material compatibility plays a particularly important role. Swelling, shrinking, or embrittlement are the most serious changes which elastomers can experience when they come into contact with lubricants [14]. There are two possible kinds of interaction, chemical (rare) and physical. During physical interactions two different, and opposing, processes may occur; extraction of soluble components out of the elastomer, causing shrinkage and absorption of the lubricant by the elastomer, causing swelling. The degree of swelling of elastomeric materials depends on the size of the lubricant (the larger the lubricant, the smaller the degree of swelling), the molecular dynamics of the lubricant (linear lubricants diffuse into elastomers quicker than branched or cyclic lubricants), the closeness of the solubility parameters of the lubricant and the elastomer (the ‘like-dissolves-like’ rule is followed), the polarity of the lubricant [15]. Presence of the polar side-groups in the backbone chain increases the oil resistance of the polymer. Crosslinking also limits the degree of polymer swelling by providing tie points (constrains) that limit the amount of solvent that can be absorbed into the polymer [16, 17].

Elastohydrodynamic lubrication (EHL) of line contacts has been studied extensively. The film thickness and friction in EHL depend not only on the viscosity of the lubricant but also on the pressure –viscosity coefficient of lubricant and the elasticity of the mating surfaces. In soft EHL, where one of the mating surfaces has low module of elasticity, the contact pressure is not very high and the viscosity is believed to be constant and the friction and film thickness depend on the viscosity of the lubricant, module elasticity of the mating surfaces and the contact geometry [18]. When one of the mating surfaces is viscoelastic, the film thickness is affected by the viscoelasticity of the surface [19].

Nitrile rubber (NBR) is a copolymer of acrylonitrile and butadiene and provides a low-cost elastomer with good mechanical properties in sealing applications. The concentration of acrylonitrile in the copolymer has a considerable influence on the polarity and swell resistance of the vulcanizate in non-polar solvents. The greater the acrylonitrile content, the lower the amount of swell in motor fuels, oils, fats, etc [20]. Acrylic rubber (ACM) is a type of synthetic rubber containing acrylonitrile. It is a copolymer of two major components: the backbone (95- 99%) and the reactive cure site (1-5%). The outstanding property of ACM rubber is its resistance to hot oil. It is more heat resistant than NBR. Its resistance to weather, ozone and natural aging is also higher than NBR but it has less resistance to wear and oil swelling than NBR [20]. Fluoroelastomers are typically used in harsh environments where other elastomers fail. Chemical resistance and heat resistance are the two main attributes that make fluoroelastomers attractive for sealing applications. FKM is the designation for a large sort of fluoroelastomers containing vinylidene fluoride as a monomer [20]. The influence of oil-elastomer interaction on the frictional behaviours of elastomeric materials, which plays an important role on seal application, has not been studied well. In this paper, the lubricated frictional behaviour of the four most commonly used sealing elastomers has been studied.

2. EXPERIMENTAL WORK

The experiments were performed using Micro-Tribometer UMT-2. A rubber specimen glued to a metal backing plate was pressed against a rotating steel ring counterface. The normal and frictional forces were recorded by high resolution strain gauge force sensors. The schematic of the test configuration is shown in Figure 1.
The dimensions of the rubber specimen were $16 \times 4 \times 2$ mm (the width of the contact area was 4 mm). The rubber samples were cut from sheets of 2 mm thickness. The outer diameter of the counterface bearing steel ring and its thickness were 35 mm and 8 mm, respectively. The rubber specimens were washed in industrial petroleum for 3 min using an ultrasonic cleaner, dried in an oven for 10 min at 40 °C. A unique ring was used in all tests and the first test repeated after all tests to ensure that its surface properties had not been changed significantly. The ring was washed in industrial petroleum for 3 min by using the ultrasonic cleaner and dried before each test. The elastomers studied during this work are commonly used seal materials, acrylonitrile butadiene rubber (NBR), hydrogenated acrylonitrile butadiene rubber (HNBR), acrylate rubber (ACM), and fluoroelastomer (FKM). All the elastomers have a module of elasticity of about 10 MPa at very low speed and room temperature. The nominal hardness, tensile strength, elongation at break, and material densities of these elastomers are given in Table 1. The surfaces of the bearing steel ring and elastomeric samples were characterized by a Wyco 3D optical surface profilometer. The typical surface topography and the range of average surface roughness (Ra) of the ring and elastomeric samples have been shown in figures 2 and 3, respectively. The experiments were carried out at a normal load of 3.5 N. Using the Hertz contact theory, the average contact is estimated to be about 370 kPa, which is of the order of the contact pressure on a new elastomeric radial lip seal. The tests were initially run for 50 minutes at a sliding velocity of 18.33 mm/s to reach more steady results and the sliding velocity was then varied as 0.24, 0.33, 0.58, 1.03, 1.83, 3.26, 5.79, 10.30, 18.33, 32.58 mm/s. The tests were run for 10 min at each sliding velocity. All the tests were performed at room temperature (22 ± 2 °C).

**Table 1: Tested elastomers and their properties**

<table>
<thead>
<tr>
<th>Elastomeric materials</th>
<th>Hardness (Shore A)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation at break (%)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrile rubber (NBR)</td>
<td>76.1</td>
<td>25.4</td>
<td>466</td>
<td>1.31</td>
</tr>
<tr>
<td>Hydrogenated nitrile rubber (HNBR)</td>
<td>71.3</td>
<td>17.5</td>
<td>303</td>
<td>1.24</td>
</tr>
<tr>
<td>Acrylic rubber (ACM)</td>
<td>73.4</td>
<td>7.8</td>
<td>171</td>
<td>1.49</td>
</tr>
<tr>
<td>Fluoro rubber (FKM)</td>
<td>72.8</td>
<td>–</td>
<td>–</td>
<td>2.03</td>
</tr>
</tbody>
</table>

*Figure 2: Surface topography of the ring (Ra = 380 nm, after removing the cylindrical term)*
3. RESULTS AND DISCUSSION

A part of the Steinbeck curve including the boundary, mixed and elastohydrodynamic lubrication regimes has been produced for sliding the ring against each elastomeric material. The results are shown in Figure 4. As shown in the figure, the friction coefficients in the second parts of experiments (when the sliding velocity decreases and the elastomeric materials have more time to interact with the lubricant) differs from the corresponding values in the first part (when the sliding velocity increases). The results show that the friction coefficients of FKM and HNBR in boundary lubrication regime increases in the second part and it may be due to the extraction some elastomers’ constituents (such as plasticizers) but the friction coefficients of NBR and ACM in boundary lubrication regime decreases in the second part that may be due to the oil absorption. The most affected elastomer by oil is ACM which is in agreement with the literature [16, 17]. In view of the frictional behaviour in boundary lubrication regime, the ACM and FKM show the best and worst behaviour, however, the ACM and NBR are the least and most oil compatible materials, respectively. Thus considering the oil compatibility and the frictional behaviour in boundary lubrication regime, the FKM and the HNBR show the worst and the best behaviours, respectively.

Figure 3: Surface topography of the elastomeric samples ($Ra \approx 80$ nm)
To see the difference of frictional behaviour of the elastomeric samples in elastohydrodynamic lubrication regime, the results are shown in a logarithmic scale in Figure 5. As shown in the figure, although the module of elasticity of elastomeric samples, lubricant and the contact geometry are the same in all experiments, the friction coefficients are different and it can be due to the viscoelastic behaviour of the elastomers. More investigation on the viscoelastic properties of the elastomers is needed to explain this difference. In contrast with the boundary lubrication regime, the FKM shows the least friction coefficient in elastohydrodynamic lubrication regime. The HNBR shows the highest friction coefficient in elastohydrodynamic lubrication regime.
4. CONCLUSIONS

The frictional behaviour of four sealing elastomers including an acrylonitrile butadiene rubber (NBR), a hydrogenated acrylonitrile butadiene rubber (HNBR), an acrylate rubber (ACM) and a fluoroelastomer (FKM), sliding against a steel surface in boundary, mixed and elastohydrodynamic lubrication regimes have been studied. The results show that in boundary lubrication regime, the ACM and FKM of the tested elastomers show the least and highest friction coefficients, respectively. However, the ACM is the least oil compatible material and thus the HNBR may be pointed as the best elastomeric material in view of both the frictional behaviour and oil compatibility. In the elastohydrodynamic lubrication regime, the friction coefficient of FKM and HNBR are the least and highest values, respectively. The results show that the friction coefficient of an elastomer in boundary lubrication regime may decreases or increases with time and it may be due to the oil absorption or extraction of some elastomer’s constituent, respectively. The friction coefficient of elastomer in elastohydrodynamic lubrication regime depends not only on the lubricant properties, contact geometry and modulus of elasticity of the elastomer, but also on its viscoelastic properties.

5. REFERENCES