Tribology International 78 (2014) 187–194

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

The effect of aging in oil on the performance of a radial lip seal

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ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form
3 May 2014
Accepted 7 May 2014
Available online 23 May 2014

Keywords:
Lip seal
Aging
Pumping rate
Friction torque

ABSTRACT

The effect of aging in oil on the seal performance of a radial lip seal is investigated in the present study by conducting a constant temperature oil bath test to obtain aged rubber samples and seals, and measuring the changes of material properties and seal performance with the aging time. The change of lip surface micro-morphology with the aging time is also measured by using a 3D white light optical interferometer. The leakage and friction torque are computed in a numerical simulation, utilizing a mixed elastohydrodynamic lubrication (EHL) model, to determine how aging in oil affects the lip seal performance. Finally, the simulation results of the EHL model are verified by a bench test on aged lip seals.

1. Introduction

Elastomeric radial lip seals are widely used in industry to retain lubrication and exclude contamination in rotating shaft and bearing applications. Fig. 1 shows a schematic of an installed lip seal and its components.

Well-designed radial lip seals do not leak significantly, unlike most other types of rotary seals such as mechanical seals and labyrinth seals. While a micron scale film of fluid lubricates the lip–shaft interface in the sealing zone, leakage is prevented by a pumping action from the air-side toward the liquid-side of the seal [1–4], produced by the asperities on the lip surface. Under dynamic conditions, the asperities on the lip surface are distorted into vane-like shapes due to the shear deformation of the elastomeric lip in the circumferential direction. In addition, under the action of the interference and the spring force, the elastic deformation of the elastomeric ring generates a contact pressure with an unsymmetrical triangle-like profile, with the axial location of maximum shear deformation closer to the liquid-side than to the air-side. This results in a net pumping of liquid from the air-side toward the liquid-side. The reverse pumping rate is the most important performance characteristic for the evaluation of the success of lip seals [5–7]. If the pumping rate is too small, the seal will leak.

Commonly, rubber is used as the material for the elastomeric ring of the lip seal since rubber has very good elasticity as well as good chemical resistance and wear resistance. However, the biggest disadvantage of rubber is that it is susceptible to aging under the influence of heat, UV radiation, oxygen, ozone, mechanical loads and exposure to mediums such as lubricants. The effect of aging during storage on the performance of a radial lip seal due to heat and oxygen has previously been reported by the present authors [8]. However, when a lip seal is in use, the seal is generally exposed to oil, so aging induced by oil is also an inevitable phenomenon. The elastomeric ring always absorbs a portion of oil, leading to swelling. Due to the swelling, the volume of the seal will increase and the interference fit between the elastomeric ring and shaft will decrease. Also, the absorption of oil will result in the reduction of the elastic modulus of rubber and hardness, i.e. the rubber will become softer [9]. These effects will affect the pumping action, ultimately decreasing the lip seal's service life. Therefore, it is important to study how aging in oil affects the performance of radial lip seals.

Most previous research efforts on the influence of aging of seals in oil are limited to the change of seal material properties. Trakarnpruk and Porntangjitlikit [10] studied the effect of aging in biodiesel (prepared from palm oil by transesterification with methanol) on the mass change, volume change, hardness, tensile and elongation and dynamic mechanical properties of six types of elastomers (NBR, HNBR, NBR/PVC, acrylic rubber, co-polymer FKM and terpolymer FKM). Their results showed that the properties of NBR, NBR/PVC, and acrylic rubber were affected more than other elastomers, due to the absorption and dissolving of biodiesel by rubber. Dinzburg and Gillen [11] used the modulus profiling technique to monitor the carbonization (hardening of the rubber

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http://dx.doi.org/10.1016/j.triboint.2014.05.017
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Nomenclature

D_i	shaft diameter
f	friction coefficient
F	cavitation index
F_r	radial force
h	nominal film thickness, separation between surface means
$\hat{h}$	dimensionless film thickness, h/σ
h_s	static undeformed film thickness
I_n	influence coefficient for normal deformation
I_s	influence coefficient for circumferential deformation
K	aspect ratio of solution space, L_x/L_y
L_x	length of solution domain in x direction
L_y	length of solution domain in y direction (contact width)
p_a	ambient pressure
p_c	contact pressure
p_{cav}	cavitation pressure
p_{ref}	characteristic reference pressure
p_s	sealed pressure
p_{sc}	static contact pressure
$\hat{p}_f$	dimensionless fluid pressure, p_f/p_{ref}
$\hat{q}_y$	dimensionless pumping rate in y direction per unit length in the x direction
$\hat{Q}_y$	dimensionless pumping rate in y direction
U	linear speed
$\hat{x}$	dimensionless circumferential coordinate, x/L_x
$\hat{y}$	dimensionless axial coordinate, y/L_y

Greek letters

δ_n	normal deformation of lip surface
δ_s	circumferential deformation of lip surface
μ	lubricant viscosity
ξ	dimensionless number, $\mu U L_x/p_{ref}\sigma^2$
ρ_f	density of the full film (uncavitated)
$\hat{\rho}$	dimensionless lubricant density, ρ/ρ_f
σ	the standard deviation of surface heights
$\hat{\tau}_{avg}$	dimensionless average viscous shear stress in the x direction, τ_{avg}/E
τ_f	shear stress due to contacting asperities
$\phi_{c.c}$	dimensionless density flow factor
$\phi_f, \phi_{fss}, \phi_{fpp}$	dimensionless shear stress factors
$\phi_{s.c.x}, \phi_{s.c.y}$	dimensionless shear flow factors
ϕ_{xx}, ϕ_{xy}	dimensionless pressure flow factors
ϕ_{yx}, ϕ_{yy}	dimensionless pressure flow factors
Φ	variable representing pressure/average density, defined by Eq. (2)

surface) process for two fluoroelastomer rubber compounds exposed to oil at 163 °C. Sirisinha et al. [12,13] and Mousa et al. [14] studied the oil resistance of different natural rubber blends from the perspective of rubber material properties. However, the change of material properties induced by aging alone cannot determine the seal service life; it only suggests the possible deterioration of seal performance. Although Jennewein and Frolich [9] studied the effect of aging in oil on the radial force from the perspective of lip seals, unfortunately they did not show the variation of seal performance itself, as characterized by the leakage and friction torque [15–17]. It is well known that the leakage is the most important indicator of lip seal failure, and the friction torque affects the wear of the sealing lip and system durability.

The effect of aging in oil on seal performance of a radial lip seal is investigated in the present study by conducting a constant temperature oil bath test to obtain aged rubber samples and seals, and measuring the changes of material properties and seal performance with the aging time. The material properties of the aged rubber samples are measured in a uniaxial compression experiment. As mentioned above, the pumping action of lip seals is determined by the lip surface asperities, so the change of the lip surface micro-morphology with the aging time is also measured by using a 3D white light interferometer. The interference fit between the lip seal and the shaft directly determines the contact characteristic at the sealing zone; its change with the aging time is obtained from measuring the inner diameters of aged lip seals. The change of material properties and interference fit is directly reflected in the radial force, which can be obtained from a test fixture for measuring the radial force. The leakage and friction torque are computed in a numerical simulation, utilizing a mixed elastohydrodynamic lubrication (EHL) model, to determine how aging in oil affects the lip seal performance. Finally, the simulation results of the EHL model are verified by a bench test on aged lip seals.

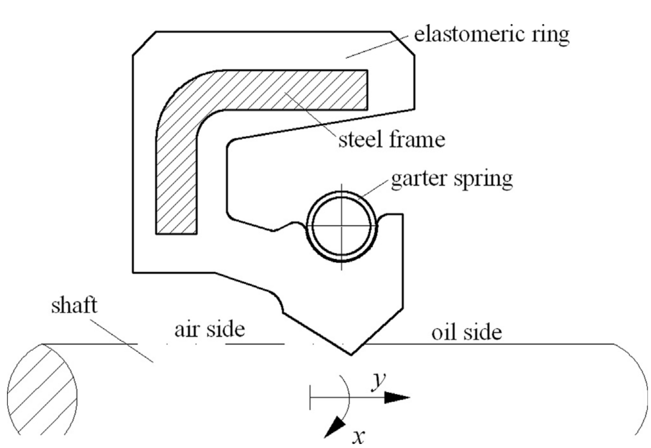

Fig. 1. Schematic of the lip seal.

2. Experimental approach

2.1. Constant temperature oil bath aging test

When a lip seal is in use, the seal is generally exposed to oil. In order to investigate how rubber aging in oil affects the sealing performance of a radial lip seal, it is necessary to exclude the influence of other factors such as sealing lip wear during use. Therefore, the constant temperature oil bath aging test is used to simulate the aging behavior and provide the aged material samples and lip seals. The samples are made of nitrile-butadiene rubber (NBR, the content of acrylonitrile is 34%, belonging to the medium and high acrylonitrile content), which is the same rubber used for the lip seals of this study. The geometry of the rubber samples is cylindrical with dimensions $\Phi 10 \times 10$ mm^2, which is used for the uniaxial compression test. The test will be discussed in Section 2.2. The lip seals have a nominal diameter of 100 mm.

During operation of a radial lip seal, the contact zone between the lip and shaft plays a decisive role in achieving sealing and essentially zero leakage. The temperature of the contact zone