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An empirical study on the breakaway friction and squeeze film effects of a polyurethane U-cup rod seal

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The influence of the dwell time and properties of oil on the breakaway friction of a U-cup rod seal was analysed. A logarithmic correlation between the breakaway friction force and the dwell time (in a range from 30 to 10^4 seconds) was found. We used oils from various viscosity classes (ISO VG 32 …460) and chemical compositions (mineral oil, silicone oil, perfluoropolyether, polyglycol). An almost linear correlation between the dynamic viscosity and the breakaway friction was found. Among viscosity and dwell time, further properties of oil must have a remarkable influence on the breakaway friction of rod seals. Using ellipsometry, we showed that even a film thickness of approximately 8 nanometres can be squeezed out of the sealing gap during dwell time.

1 Introduction

The friction of reciprocating seals is crucial for a sensitive and immediate response of hydraulic or pneumatic cylinders and control valves. In particular for precision positioning equipment, the friction of reciprocating seals is an important parameter influencing the performance of the whole machinery.

A key parameter influencing the dynamic friction of rod seals are the lubrication conditions and the film thickness in the sealing gap [1]. Additionally, Nau and Müller [2] mention influencing factors such as the surface roughness, wear conditions, particles which are dragged in the gap, contact pressure and intermolecular forces between the rod, seal and lubricant.

At onset of sliding motion, the breakaway friction (static friction) must be overcome. In general, the breakaway friction is higher than the dynamic friction [2]. With increasing dwell time (stopping time) of the seal, the breakaway friction increases [3], [4]. It must be assumed that the thin oil film in the sealing gap is squeezed out compromising proper lubrication and thus increasing friction [5]. Among the dwell time, the influence of parameters such as the sealing material [3], [6], lubricant [7] and counter face [8] on the breakaway friction was observed.

In previous papers [9]–[12], we showed that the oil film formation of common polyurethane U-cup rod seals is only in the nanometre range. If this thin oil film is squeezed out at the reversal (start/stop) positions, we must assume a remaining oil film thickness of a few nanometres only. The experimental analysis of such thin films is challenging but of great interest, since the lubrication conditions in the sealing gap have great influence on the dynamic and static friction of rod seals.

For modelling squeeze film effects between two parallel plates, the Reynolds equation can be used, see [13]. Then, the only property of the oil which is considered is the viscosity. CHAN [14] showed that the accuracy of the REYNOLDS equations decreases remarkably for lubrication films with a thickness less than 10 nm. According to PERSSON [15] who refers to a study from GEE [16], thin films with a thickness in the range of a few molecule diameters cannot be squeezed out of a lubrication gap completely. GEE mentions the molecular structure and intermolecular forces as causes of this phenomenon. Properties of liquids in narrow gaps can differ from their bulk properties [17] and might not be considered as fluids [18]. Such differences have their roots at interfacial phenomena and the surface energy of the participating phases. Further empirical studies indicate correlations between wetting properties which result from the surface energy and the static friction of tribological contacts [17], [19]–[22].

Tribological mechanisms in the sealing gap of rod seals can neither be modelled accurately nor be predicted with satisfying result. The use of a constant friction coefficient is in general not suitable [2], [23]. This paper is a step towards better understanding of mechanisms in the sealing gap of rod seal and their influence on the breakaway friction.

We present a new measurement procedure for determining the breakaway friction of rod seals after a certain dwell time. It was our aim to introduce a method with low empirical effort which can be adopted to compare the influence of the dwell time, viscosity and chemical composition of the lubricant on the breakaway friction of rod seals. Therefore, we used a recently developed test rig with a simplified design. Results from a first empirical study on the breakaway friction are presented. To analyse the squeeze out of the oil film in the sealing gap, we used ellipsometry in this study. It was possible to confirm experimentally that even thin films in the single digit nanometre range can be squeezed out of the sealing gap and that such squeeze film effects can be analysed using ellipsometry.

2 Materials

In this chapter, we describe the components of the used sealing systems, the test rig for analysing the friction of reciprocating seals and the ellipsometer for film thickness measurements.

2.1 Components of the analysed sealing system

A sealing system consists of at least three components: the sealing ring (e.g. U-cup), the lubricant (oil) and the counter face (rod).

We used a commercially available U-cup for a rod diameter $d = 50\ \mathrm{mm}$ as a sealing ring. The U-cup is named T20 (50 x 65 x 10) and was manufactured by Freudenberg Sealing Technologies GmbH. The sealing material (AU V142) is a typical polyurethane with a hardness 95 Shore A. The length of the contact between the rod and the seal in axial direction $l_\mathrm{c} = 0.91\mathrm{mm}$ and the radial load $F_\mathrm{rad} = 531\ \mathrm{N}$ were adopted from a previous study [1].

It was our aim to choose lubricants with different viscosities and different wetting properties. Pure mineral oils with various viscosity classes (ISO VG 32 … 460) were used as lubricants to analyse the influence of viscosity on the breakaway friction. These mineral oils are reference oils from a German research association named ‘Forschungsvereinigung Antriebstechnik e. V.’ (FVA), see [24] for details. Furthermore, we carried out measurements using lubricants with different chemical compositions. A polyethylene glycol PG 400 (CAS-Nummer: 25322-68-3), a silicone oil OKS 1010/1 (OKS Spezialschmierstoffe GmbH) and a perfluoropolyether (PFPE) LVO 400 (Leybold GmbH) were chosen. The chosen oils have different surface energies and wetting properties which can have an influence on interfacial phenomena and the resulting friction forces of rod seals. The viscosities were measured using a plate to plate rheometer at a shear rate of $\dot{\gamma} = 100\ \mathrm{s}^{-1}$. The surface energies of the oils were determined using bubble pressure tensiometry and the pendant drop method, as described in DIN 55660 [25], [26]. Table 1 lists properties of the used lubricants.

Table 1: Properties of the used lubricants at room temperature ($\vartheta = 22\ °C$) including the dynamic viscosity η, the surface energy σ, and the polarity χ_p.

Lubricant	**Base oil**	$\frac{\eta}{\mathrm{mPa\ s}}$	$\frac{\sigma}{\mathrm{mN\ m^{-1}}}$	$\frac{\chi_\mathrm{p}}{(-)}$
ISO VG 32	mineral oil	64	30.1	0.27
ISO VG 46		103	30.3	n/a
ISO VG 68		143	30.6	n/a
ISO VG 100		250	31.6	0.26
ISO VG 460		1317	33.1	0.27
PG 400	polyglycol	100	44.7	0.51
OKS 1010/1	silicone oil	92	20.3	0.26
LVO 400	perfluoropolyether	233	17.8	0.33

A hard chrome plated hydraulic rod was polished to a mirror smooth surface resulting in a roughness $R_\mathrm{z} = 0.1\ \mu\mathrm{m}$ and $R_\mathrm{a} = 0.01\ \mu\mathrm{m}$. The smooth surface was required for film thickness measurements using ellipsometry. The same rod was already used in previous studies on the oil film formation of rod seals [1], [9]. Compared to specifications for counterfaces of rod seals, the surface of the used rod is assessed to be smooth. However, it is known that the roughness of a surface might decrease since the seal polishes the surface during long term operation, e.g. [27], [28]. Thus, such smooth surfaces have practical relevance.

2.2 Test rig for rod seals

We recently developed a simplified test rig for the analysis of reciprocating rod seals. The test rig is shown in Figure 1 (left) and was already described in a previous paper [1]. The test rig consists of a linear actuator to facilitate the axial movement and to simulate an outstroke or instroke. The resulting friction force of the rod seal is measured using the force transducer.

It was our aim to keep the test rig as simple as possible. Both the rod and the seal ring can be dismantled from the test rig with less effort. This is necessary for film thickness measurements using ellipsometry. We did not include a pressure chamber because the test rig was not intended for analysing the influence of operating pressure. Instead, this simplified setup is ideally suited when the lubricant must be varied, since the few components of the test rig can be cleaned easily.

2.3 Ellipsometer for film thickness measurements

For the analysis of the film thickness we used the same ellipsometer as in our previous studies. The ellipsometer is equipped with a rotation unit to enable film thickness measurements in circumferential direction, see Figure 1 (right). The accuracy of the ellipsometer was validated in a previous study, see [12]. In addition, we carried out film thickness measurements on the hydraulic rod after cleaning it properly with solvent. On the clean rod without an oil film, the ellipsometer indicated a film thickness $h_\mathrm{o} < 1\,\mathrm{nm}$, which validates the zero point.

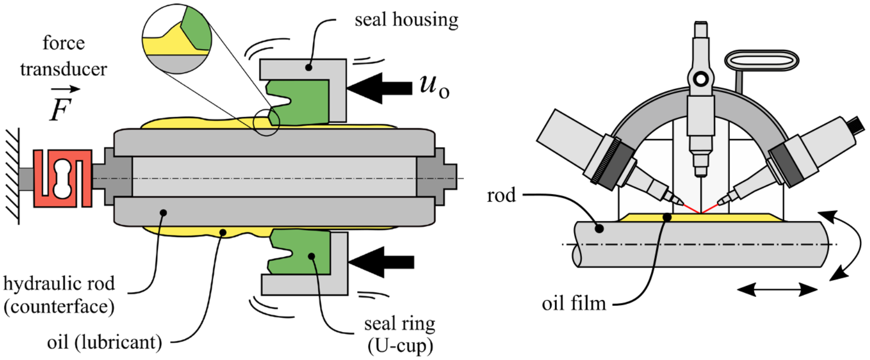

Figure 1 A schematic of the test rig for analysing the breakaway friction of rod seals (left) and a schematic of the ellipsometer for film thickness measurements (right); figures adapted from [1], [9], [10]

3 Methods

We introduce the method for measuring the breakaway friction of rod seals using the new test rig and the procedure for analysing the film thickness of rod seals.

3.1 Determination of the breakaway friction

The breakaway friction force was measured using the test rig which is described in Section 2.2. After a certain dwell time (stopping time/ rest phase) the seal housing was moved by the linear unit with a predefined speed $u_\mathrm{o} = 10\,\mathrm{mm\,s^{-1}}$ and an axial distance $\Delta x = 20\,\mathrm{mm}$. Both the speed and sliding distance were chosen after preliminary tests to ensure comparable lubrication conditions prior to each individual friction measurement. The friction force of the rod seal was measured using the force transducer. Figure 2 shows the measured friction against the relative displacement of the linear actuator in an exemplary way.

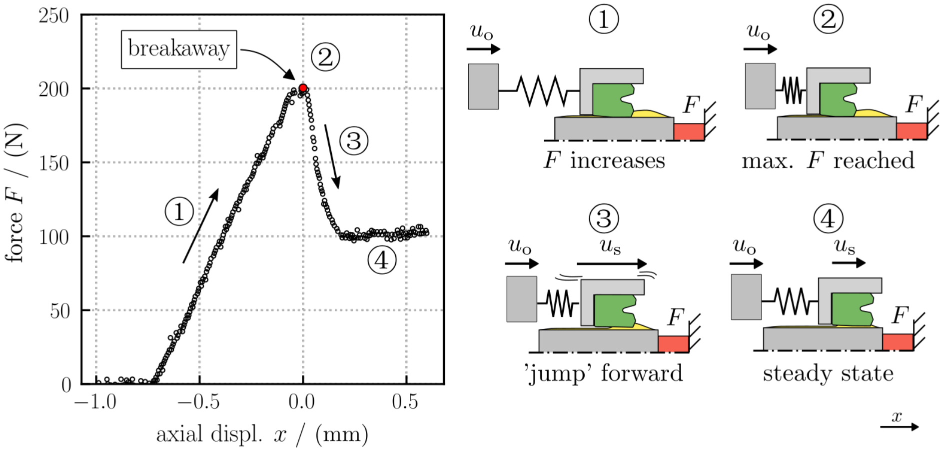

Figure 2 Measured friction force during the measurement procedure

With moving linear unit, a continuous increase of the measured friction $F(x)$ force can be observed ①. The seal ring and components of the test rig are stressed axially and compressed while the speed of the seal ring $u_s = 0$ is still zero. When the breakaway force ② of the sealing system was reached, the seal 'jumps' forward and the measured force drops remarkably ③. The maximum measured force equals the breakaway force of the sealing system, per definition. Temporarily, the relative speed between the rod and the seal ring is higher than the predefined speed of the linear actuator, $u_s > u_o$. Then, an almost constant force ④ is measured due to the constant sliding speed $u_s = u_o$ and steady state conditions.

After the determination of the breakaway friction for a certain dwell time, further measurements on the same rod can be carried out automatically (without a new setup). In this study, we carried out up to 10 measurements with various dwell times in one measurement series.

3.2 Film thickness measurements

The test rig and the ellipsometer were used for the film thickness measurements on the rod after an outstroke. In a first step, a proper amount of oil was wiped onto the rod. Thus, a fully flooded inlet zone and common lubrication conditions in the sealing gap were achieved during outstroke, see Figure 1. After an outstroke including several rest phases, the rod was dismantled from the test rig. Then, we analysed the remaining oil film thickness on the rod in the area where the rod seal was at rest during the dwell time. Therefore, multiple film thickness measurements were conducted in axial direction of the rod. It is noted, that the time delay between the oil film formation and the film thickness measurements is not critical, since such thin films do not drip off or change their thickness rapidly, see [12] for further discussion.

4 Results and Discussion

The measured breakaway friction forces and film thickness measurements of a hydraulic rod were presented including a short discussion of the results.

4.1 Breakaway friction

The breakaway friction was analysed for dwell times t in the range of $30\,\mathrm{s}$ up to $10.000\,\mathrm{s}$ $(2\,\mathrm{h}\;46\,\mathrm{min})$. The measurements were carried out at room temperature and without operating pressure. Various mineral oils (ISO VG 32 … 460), one polyglycol (PG 400), one silicone oil (OKS 1010/1) and one perfluoropolyether (LVO 400) were used as lubricants.

Figure 3 (left) shows the breakaway friction as a function of the dwell time for different lubricants. For each lubricant, one measurement series (on the same rod without a new setup) including different dwell times was carried out. The breakaway force depended on the lubricant and on the dwell time. Logarithmic model functions were fitted to the measurement data for illustration purposes. An almost linear correlation between the breakaway friction and the logarithm of the dwell time was observed. This correlation holds for the mineral oil, polyglycol, silicone oil and perfluoropolyether which have different viscosities, chemical compositions and wetting properties.

Figure 3 (right) shows the breakaway friction of the rod seal as a function of the dynamic viscosity of the used lubricants. More than 10 measurement series were conducted for each lubricant. Before setting up the test rig for each measurement, both the rod and the seal ring were cleaned with solvent. The results obtained with the mineral oil can be approximated by a linear model function.

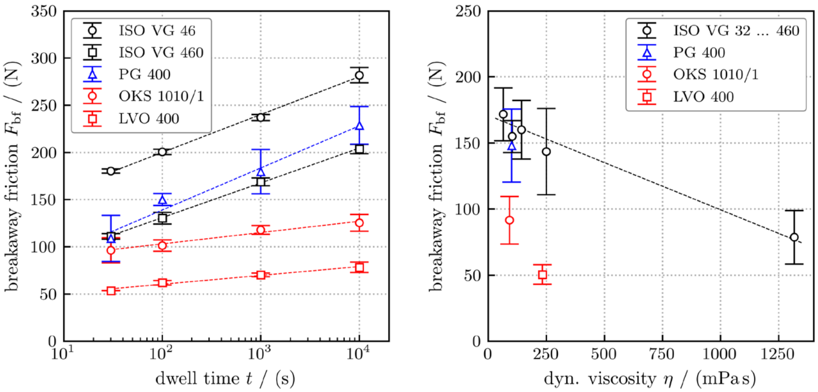

Figure 3 Measured breakaway friction as a function of the dwell time (left) and as a function of the dynamic viscosity after a dwell time of 30 s (right)

The difference between the polyglycol and the mineral oil was low in this study. However, the friction force was remarkably lower when using the silicone oil or the perfluoropolyether compared to rod seals lubricated with mineral oil or the polyglycol. Consequently, it must be noted that the chemical composition of the lubricant can have a remarkable influence on the breakaway friction force.

The used lubricants differ with respect to their surface energies and wetting properties. Using mineral oil and polyglycol as lubricants, similar friction forces were obtained, even though their wetting properties differ remarkably. However, when using the lubricants with low surface energy namely the silicone oil and perfluoropolyether, the breakaway friction forces were remarkably lower. Based on those results, it is not possible to confirm a direct and general correlation between wetting properties of a lubricant and the breakaway friction force. But it must be noted, that both silicone oil and perfluoropolyether are good choices for reducing the breakaway friction of rod seals.

4.2 Squeeze out of the lubricant

Using ellipsometry, the remaining film thickness on the rod was analysed. The measurements were conducted in axial direction and in the area where the seal was at rest during dwell time.

Figure 4 shows the measured film thickness on the rod when FVA 3 mineral oil was used and the dwell time was $t = 100\ \mathrm{s}$. The raw data (black points) was smoothened using a Savitzky-Golay-Filter (red line) for illustration purposes.

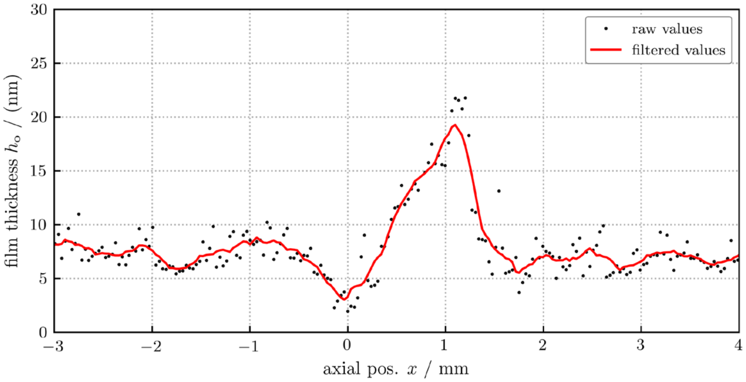

Figure 4 Measured film thickness on the rod where the seal was at rest during dwell time to demonstrate the squeeze out of the lubricant

For $x < -1\ \mathrm{mm}$, the film thickness is in the range of $\mathrm{h_o} = 8\ \mathrm{nm} \pm 2\ \mathrm{nm}$. Then, the film thickness drops to a minimum of $\mathrm{h_o} = 2\ \mathrm{nm}$ at $x = 0$ followed by an increase up to a maximum of $h_o = 22\ \mathrm{nm}$. After the maximum, the film thickness drops again with increasing x. An almost constant film thickness $\mathrm{h_o} = 8\ \mathrm{nm} \pm 2\ \mathrm{nm}$ was observed for $x > 1.5\ \mathrm{mm}$, which is similar to the initial value for $x < -1.0\ \mathrm{mm}$.

It is assumed that during the dwell time, the seal ring partially squeezed out oil from the sealing gap (contact between the rod and the seal). The contact area or sealing gap was located in the range of $-0.8\ \mathrm{mm} < x < 0\ \mathrm{mm}$ where the film thickness is reduced. The length of the reduced film thickness corresponds approximately to the contact length $l_\mathrm{c} = 0.91\mathrm{mm}$ between the seal ring and the rod which was determined using a hollow glass rod in advance, see [1]. After overcoming the breakaway friction force, the seal ring 'jumps' in axial direction. In this phase, the relative speed between the rod and the seal ring is greater than the predefined speed of the linear actuator u_o. Due to the fact that the oil film formation of such U-cups is a function of the rod speed [9], the local increase of the film thickness is plausible. Aside, it can be seen that within an axial distance of approximately twice the contact length ($\Delta x \approx 1.8\ \mathrm{mm}$), the oil film thickness has reached a constant value and obviously the dynamic sealing gap was formed.

The results confirm that during dwell time the film thickness in the sealing gap of such U-cup rod seals does not exceed the single digit nanometre range. Figure 4 indicates a film thickness of only $h_\mathrm{o} = 2\ \mathrm{nm}$ after a dwell time $t = 100\ \mathrm{s}$ and when using an oil with a dynamic viscosity $\eta = 250\ \mathrm{mPas}$ (ISO VG 100 at room temperature). When using oils with lower viscosities, the film thickness on the rod was only in the low single digit nanometre range. It was therefore not possible to identify a contact point where the film thickness was significantly reduced and oil was obviously squeezed out.

From a scientific point of view two challenges arise. For the empirical analysis of the film thickness in the sealing gap of common rod seals at common operating conditions, a resolution in the sub nanometre range might be required. This means that the static sealing gap has a height of only a few molecular layers. Consequently, when modelling tribological mechanisms in such thin gaps the use of approaches based on continuum mechanics and the Reynolds equation might not be accurate. In such narrow gaps, the influence of intermolecular forces between the lubricant and the counter faces have a significant influence on resulting friction forces. This is what we know as the boundary lubrication regime, see [29]. Results shown in Figure 3 (b) seem to confirm our conclusion since differences between the measured friction forces can not be explained by a time and viscosity dependent squeeze out of the different lubricants.

5 Summary and Conclusion

This paper is a step towards better understanding of lubrication mechanisms and breakaway friction of reciprocating rod seals. We introduced a measurement procedure for analysing the breakaway friction of rod seals and squeeze film effects in the sealing gap by measuring the remaining film thickness on the rod.

It was shown that the breakaway friction increases with the logarithm of the dwell time. This correlation was shown for oils with various chemical compositions which were used as lubricants. Using mineral oils, an approximately linear correlation between the dynamic viscosity and the breakaway friction was observed. However, the breakaway friction does not only depend on the dwell time and the dynamic viscosity. When using oils with different chemical compositions and wetting properties, differences regarding the breakaway friction were observed, e.g. the breakaway friction forces of the rod seals lubricated with silicone oil and perfluoropolyether were remarkably low.

The squeeze out of oil in the sealing gap of a common U-cup rod seals after a certain dwell time was measured successfully using ellipsometry. It is remarkable that the film thickness was only in the low single digit nanometre range. Consequently, tribological mechanisms in the sealing should be modelled on an atomic scale.

In general, the methods presented can be adopted for the analyses of further reciprocating sealing solutions for hydraulic and pneumatic applications. A combination of friction and film thickness measurements is helpful for gaining better understanding of mechanisms in the sealing gap of rod seals.

6 Nomenclature

Variable	***Description***	***Unit***
d	Diameter	$[\mathrm{mm}]$
F	Friction force measured at the test rig	$[\mathrm{N}]$
F_{bf}	Breakaway friction (static friction) of a rod seal	$[\mathrm{N}]$
F_{rad}	Radial load of a seal	$[\mathrm{mm}]$
h_{o}	Film thickness on the rod after an outstroke	$[\mathrm{nm}]$
l_{c}	Axial length of the contact between rod and seal	$[\mathrm{mm}]$
R_{a}	Arithmetical mean roughness (ISO 4287)	$[\mathrm{\mu m}]$
R_{z}	Mean roughness depth (ISO 4287)	$[\mathrm{\mu m}]$
t	Dwell time / stopping time during outstroke or instroke	$[\mathrm{s}]$
u	Speed	$[\mathrm{mm\ s^{-1}}]$
u_{o}	Rod speed at an outstroke	$[\mathrm{mm\ s^{-1}}]$
u_{s}	Relative Speed between the rod and the seal ring	$[\mathrm{mm\ s^{-1}}]$
x	Displacement in axial direction of the hydraulic rod	$[\mathrm{mm}]$
η	Dynamic viscosity of a fluid	$[\mathrm{mPa\ s}]$
σ	Surface energy of a fluid	$[\mathrm{mN\ m^{-1}}]$
ϑ	Temperature	$[^{\circ}\mathrm{C}]$
χ_{p}	Polarity of a fluid	$[-]$

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