Understanding the Dynamic Influences of Gear Oils and Radial Shaft Seals

Matthias Adler, Joe Walker, Sascha Grasshoff, Craig Desrochers and Matthias Pfadt

Introduction

Sustainability is becoming one of the most important aspects within the power transmission business. Users demand low-maintenance drive systems with as little disruption as possible, and expect lifetimes of more than 10,000 hours. Approximately 40 percent of long-term gearbox leakages can be traced back to poor interaction between the radial shaft seal (RSS) and the lubricant. Thus, it becomes essential to analyze the tribological system as a whole, which includes the gear oil, seal grease (if required), elastomer material and design, and the shaft. This paper highlights the most critical interactions between the industry's most commonly used gear oil formulations, with emphasis on synthetic oils featuring nitrile- and fluoro-elastomers. Described here are wear modes for radial shaft seal (RSS), such as the change of dimension, seal lip wear, and shaft run-in.

This report also offers evidence of how polarity of the base oils and additives alters swelling and shrinking behavior, which will eventually impact upon the sealing function. Chemical and physical reactions between lubricant and elastomer were space-resolved with the help of image-scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) analysis, as well as nuclear magnetic resonance (NMR). Through the newest micromechanical measuring system developments, one was able to determine the difference of the mechanical properties in the sealing lip area within μm. It was proven that certain oil formulations merely changed the mechanical properties on the surface of the RSS. Typical immersion testing would not show any significant differences regarding the mechanical properties, but under long-term dynamic testing those oil formulations show considerable wear, and eventually leakage, of the RSS. It was proven that with an ideal combination of base oil and additives, the latest demands of life expectancy on the radial shaft seals can be met.

Functional Principle of the Simmerring Seal (Radial Shaft Seal)

Radial shaft seals are generally used to provide a dynamic seal for rotating shafts (Fig. 1-a). The sealing mechanism is a complex, dynamic interaction (Fig. 1-b) — as opposed to a simplistic static closure of the gap between the shaft and bore (Ref. 1).

The dynamic sealing mechanism is influenced by shaft surface, design of the sealing lip, viscosity and the wetting behavior of the lubricant, as well as the macro- and micro-mechanical properties of the elastomer. The sealing mechanism is based on the pumping effect of the lubricant in the sealing gap. The seal fulfills its function when the lubricant between shaft and sealing edge is completely extracted back (Ref. 2).

A sufficient supply of lubricant to the seal is crucial for the service life and reliability of the seal. The more intensive the lubrication, the lower the wear. Even when stationary, the medium to be sealed, which at the same time is used for lubrication, penetrates the uneven areas of the shaft and
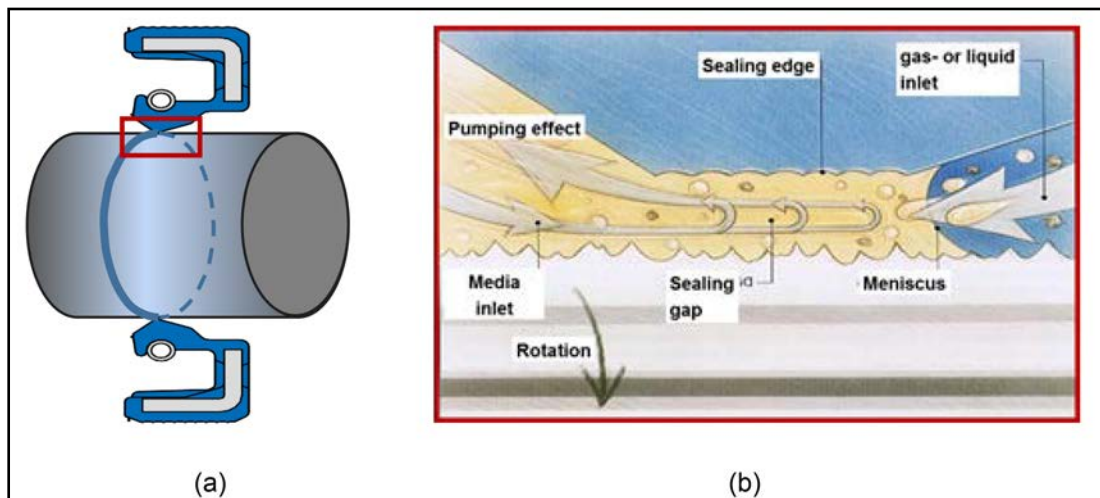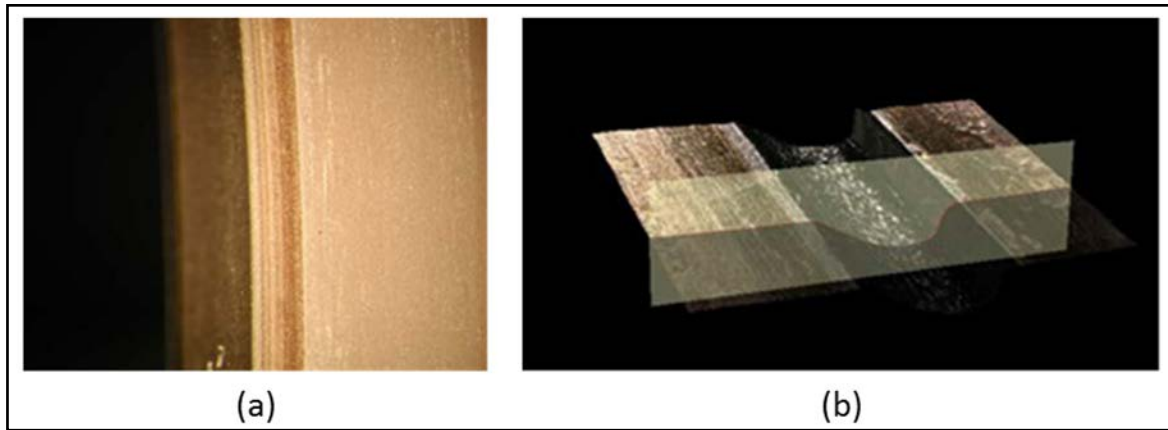

Figure 1   Radial shaft seal tribological system.

Figure 2   (a) View after 1,000 hours dynamic testing of the sealing edge (sealing edge wear with grooving); (b) magnified view of a shaft, showing shaft wear in the seal lip area.

sealing lip due to capillary forces. However, the direct contact of the sealing lip with the shaft predominates. Initial and then larger rotary movements produce a change, similar to a plain bearing, from a state of startup friction through mixed friction to predominantly hydro-dynamic friction. The seal must not run dry under any circumstances. Therefore when fitting the seal, lightly grease or oil the shaft and seal. The medium to be sealed is not only a lubricant, but also a coolant that draws off heat produced by friction.

The shaft, as part of the tribological system, influences the micro pumping action as well. Only a lead less surface finish can guarantee the leak free bidirectional operation. However, lead can assist in a unidirectional setup, when the thread's direction coincides with the pumping movement.

Boundaries for the functionality of the seal are also set by the roughness and hardness of the shaft; industry standards are available from industry leading manufacturers. Roughness and film thickness, which are, among others, pressure-dependent, and velocity and viscosity, are set by the application and therefore are not discussed further in this paper.

The following discussion highlights the interaction between lubricant and elastomer under a hydrodynamic scenario.

As the shaft surface and sealing edge move against each other, wear is introduced in the contact zone. This wear can either occur on the sealing lip (Fig. 2-a), the shaft (Fig. 2-b), or both. Figure 2-a is a magnified view of the sealing edge after 1,000 hours of dynamic testing. This sealing edge is showing edge wear with grooving.

This wear will eventually lead to a leaking application. Thus, to reduce the wear it is beneficial when a lubricating film is established between the RSS and the shaft. Wear reduction is also a function of the pumping effect.

In the following paper, basic mechanisms of the lubricant — elastomer interaction as well as methods to characterize those — will be described. There will be a principal distinction between physical and chemical interactions (Ref. 3).

Physical Interaction

Physical interactions between lubrication and sealing materials focus on diffusion/exchange interactions, as well as the wetting behavior between the elastomer and the lubricant.

Diffusion processes. Elastomers and lubricants are blends of different chemical compounds that are designed to meet a specific task in their respective system. The elastomer consists of a basic polymer; fillers; plasticizers; antioxidants; cross-linking additives; and processing aids. The lubricant consists of a base oil, additives, and for a grease, a thickener system. These additives could include a combination of extreme pressure (EP) additives, anti-wear (AW) additives, antioxidants, viscosity improvers (VIs), and corrosion protection. These additives and base oils all differ in their molecular size and polarity as well.

Recognizable is the significant difference in the polarity within the elastomer types ACM, NBR, and FKM, as well as the differences within the lubricant types: mineral (Min), polyglycol (PG) oil, and polyalfaolefines (PAOs). The additives, used in both elastomer as well as lubricant, tend to be polar. The majority of synthetic industrial gear oils consist not only of a single base oil, but also a blend of base oil chemistries. In oils where additive solvency is difficult, esters or methacrylates can be used to keep the additives dissolved in the oil. The mixture of opposing base oils is also important to
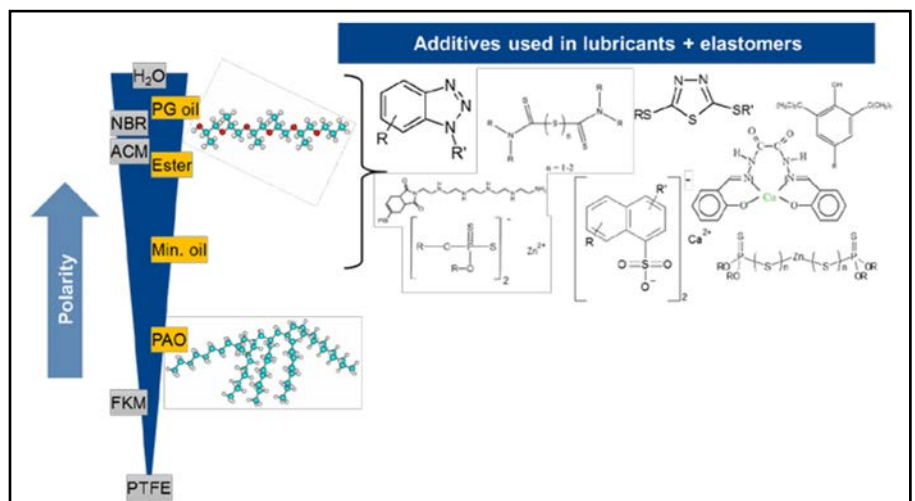
Figure 3   Qualitative comparison of polarity between lubricant and elastomer components.

the compatibility with elastomers. Pure PAO base oils tend to shrink most types of elastomer types; ester will swell those elastomers, for example. The combination of these two oils in the correct ratios can negate the end effect on the elastomer. This formulation is a careful process in mating the correct ratios of additivation, base oil chemistries, and concentrations to develop a market-ready gear oil.

Polarity is the most important factor for the solubility of a chemical compound in a different chemical compound, such as the solubility of an antioxidant in a base polymer or in the base oil of a lubricant (Ref. 4).

When a multi-component system, such as the elastomer of the RSS, makes contact with another multi-component system, such as the lubricant, diffusion processes can take place that are driven by a concentration difference of the additives in the elastomer matrix and the lubricant. Compounds diffuse in the system, which has a similar polarity. Thus, non-polar elastomer components from the polar NBR can diffuse in a non-polar mineral or PAO lubricant. The result is a volume decrease of the elastomer. One can observe a volume swell when polar components of the lubricant, such as EP and AW additives, diffuse in the polar NBR. Another possibility is that the same number of molecules diffuse from the elastomer into the lubricant, and vice versa; in that case a volume change cannot be measured. However, the elastomer changed its chemical structure; the processes are displayed schematically (Fig. 4).

Temperature and molecular size can also influence the duration of the diffusion process. Test specimens and RSS of various NBR compounds were stored under 40°C at 500 hours in different PAO oils; the volume of oil bath was 80 times the volume of the rubber. Volume changes of the test specimen were measured according to DIN 53521. Additionally, the change of the inner diameter of the RSS, thus the interference with the shaft, was recorded. Observed were significant volume change differences of the tested PAO/NBR combinations.

Figure 5 displays the volume change measured on test specimens versus the corresponding change of the inner diameter of the radial shaft seal. This illustrates that there is a direct correlation between the volume increase of the test specimen and the inner diameter of the RSS, and vice versa. Therefore, it is possible that the interference and the radial
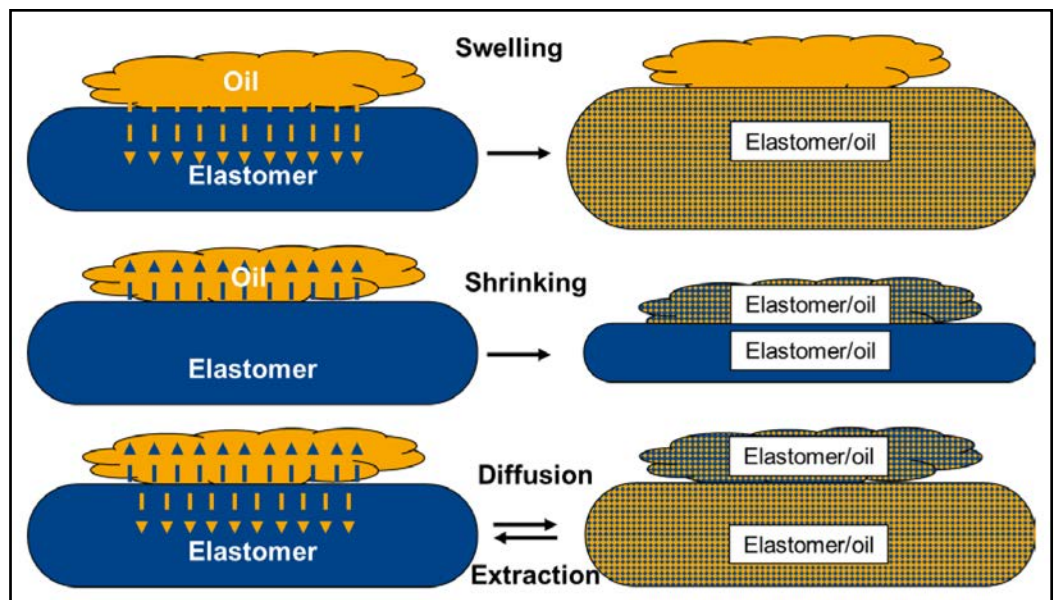

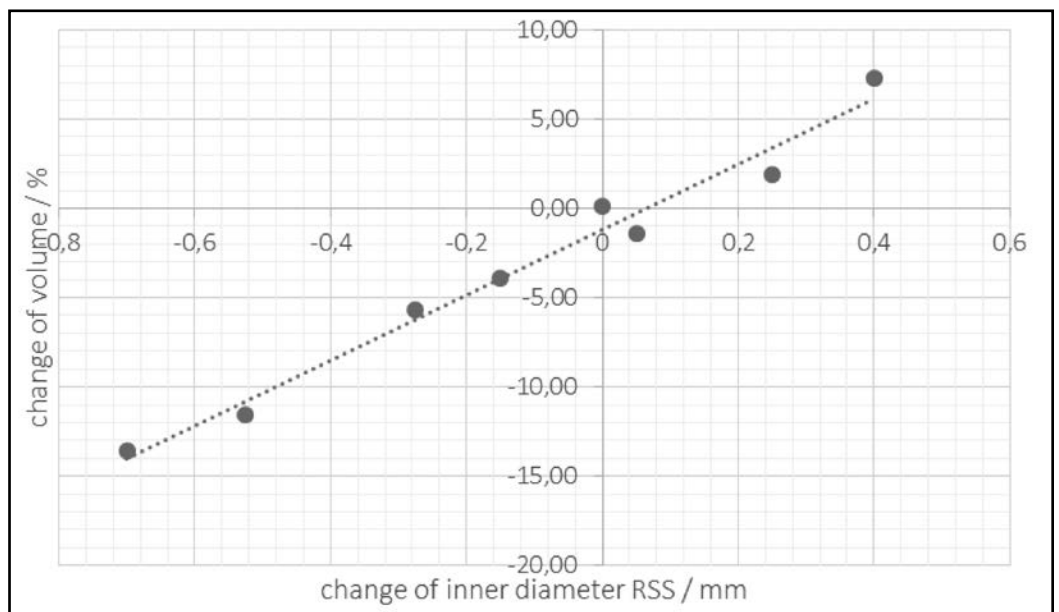**Figure 4   Schematic display of the three basic physical diffusion processes between lubricant and elastomer.**

Figure 5   Correlation of the NBR RSS inner diameter change with the volume change after static tests in different PAO oils for 500 hours at 40° C.

force of the RSS significantly increases when shrinkage occurs. This could cause an increase of friction, which increases the thermal stress under the sealing lip, which results in higher wear. If swelling occurs, the RSS interference, thus radial force, decreases on shaft. If the swelling comes to a point where the inner diameter (ID) of the RSS is equal or greater than the shaft diameter, leakage occurs.

Diffusion processes not only change the dimensional parameters of the seal — they also change the chemical composition. This could be proven by examining the chemical composition of NBR RSS after static tests in different lubricants. Two-mm-thick NBR test panels were stored in various base oils and fully formulated oils for 1,000 hours at 90°C; the volume of the oil bath was 80 times the volume of the rubber. Afterwards, the NBR test panels were extracted under reflux with an acetone/n-hexane solution. The extract was analyzed through a gas chromatography–mass spectrometry (GS-MS) and the compounds qualitatively specified (Ref. 5). Figure 6-a displays a GC-MS spectrum of an extract of a NBR compound. Here, antioxidants (AO), plasticizer (Piast), and processing aids have been detected.

Figure 6-b displays the GS-MS spectrum of a PAO oil of an NBR compound after storage in a pure PAO base oil. One can recognize that most NBR additives are diffused in the oil.

Figure 6-c shows the GS-MS spectrum of an extract of an NBR compound after storage in an additiveenriched PAO oil. One can recognize that many oil components are diffused in the elastomer. To a point, those additives are capable of starting a chemical reaction with the elastomer.

The additives' diffusion behavior between lubricant and elastomer is not only determined by polarity, but mobility as well. Mobility is defined by the molecular size and the reactivity of an additive. A phosphor-rich AW additive might only react on the surface and not pass the outer layer of the seal; thus it would not change the elastomer matrix.

Figure 7 shows image scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM- EDX) pictures of NBR specimens, stored for 1,000 hours at 90°C in two different, additive-rich PAO oils; the volume of the oil bath was 80 times the volume of the rubber. The yellow area indicates the phosphor-rich section of the elastomer.

The results above suggest that it is necessary to coordinate the elastomer formula with the lubricant composition to achieve the best possible interaction. Therefore, close cooperation in the development of lubricant and elastomer is crucial.
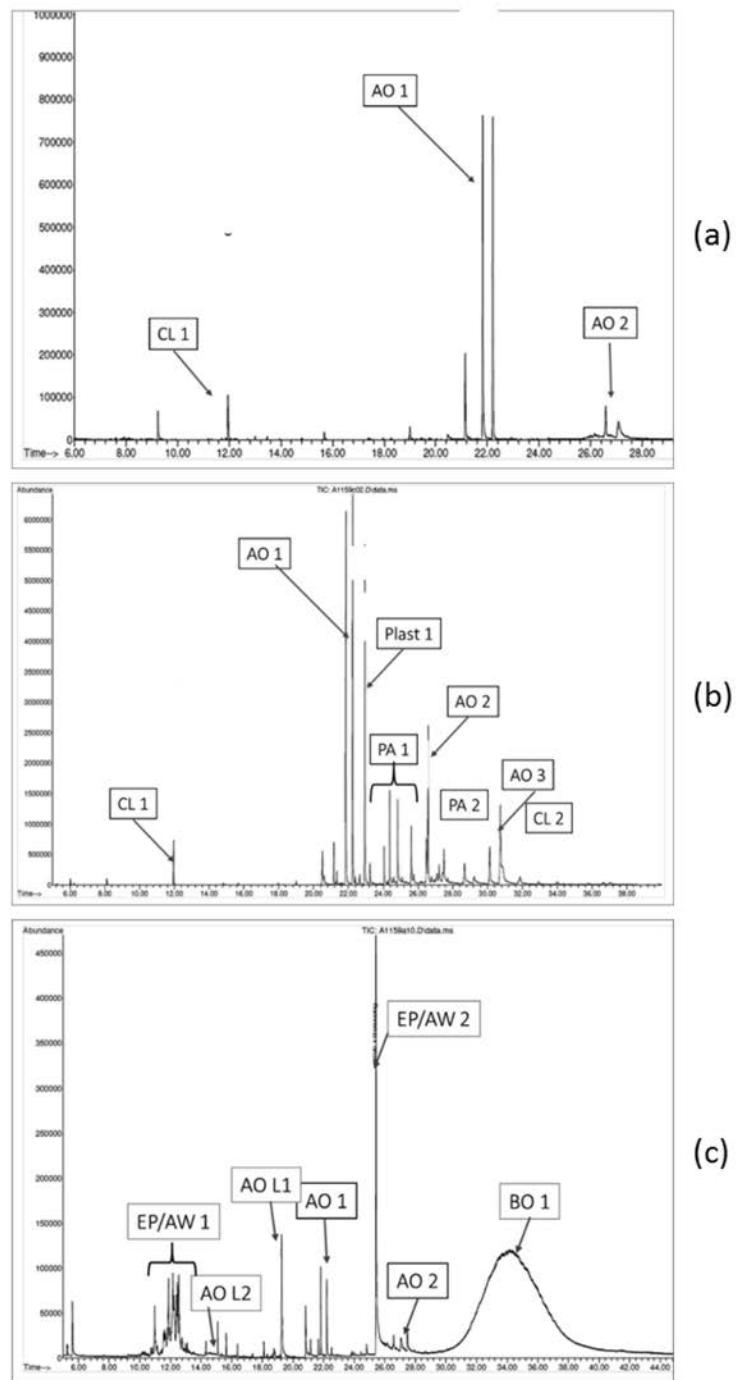
Figure 6   Characterization of elastomer extracts/oils with GC-MS of NBR compounds after static storage in different oils: (a) extracts of pure NBR; (b) NBR after storage with pure PAO oil; (c) NBR after storage in full additive PAO oil.
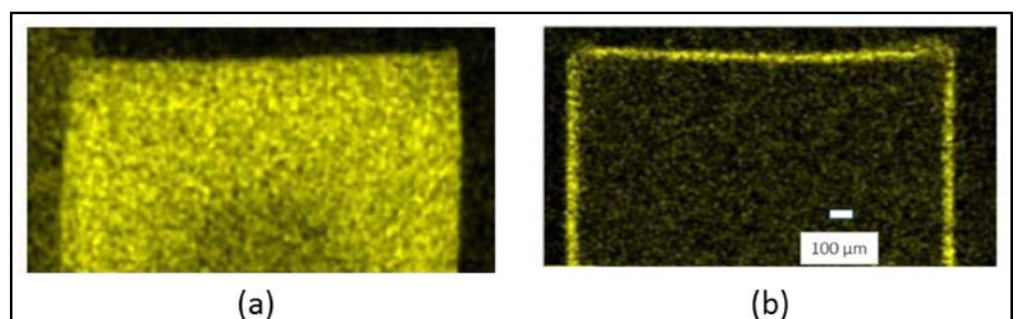
Figure 7   SEM-EDX analysis of a 2-mm NBR specimen cross-section in two different PAO oils, yellow highlighted are the phosphor concentrations.

Wetting behavior. The wetting behavior is another important physical interaction between the lubricant and the elastomer. It describes the ability of a lubricant to generate a joint surface with an elastomer or metal (Ref. 6).

One can define the wetting behavior through the measurement of the contact angle that a drop of lubricant creates with the elastomer surface Figure 8-a, according to DIN 55660-2 (Dec., 2011).

Where the lubricant has a poor wetting behavior, the contact angle will be large (Fig. 8-b); in the case of a good wetting behavior, the contact angle will be smaller.

When the lubricant has a poor wetting behavior with the elastomer, the lubricant will not penetrate well into the sealing gap (Fig. 9-a). Poor wetting of the sealing edge also suggests a higher probability of insufficient lubrication under the sealing lip — thus suggesting an increase of wear on the sealing edge and/or the shaft. The better the wetting behavior, the better the coverage will be in the sealing gap (Fig. 9-b).

One of the major factors that determine wetting behavior is the polarity difference between lubricant and elastomer. The combination of polyglycol gear oils and FKM seals is widely spread on the market for specialty and high-temperature applications, although it is challenging in terms of wetting the seal edge and a non-optimized system can lead to more wear on the sealing edge and/or shaft (Fig. 10).

The wear pattern of approximately 1 mm (Fig. 10) can be minimized through additional features such as pre-greasing the seal with an appropriate grease and geometrical modification of the seal itself. Figure 11 shows three possibilities targeting the optimal wear characteristics.

In Figure 11-a a different FKM compound with a modified pumping effect was used to improve the wetting behavior of the system, thus reducing the wear.

Figure 11-b shows the original FKM, but pre-lubricated with a grease on the air side, which features good compatibility with PG oils and FKMs. The wetting behavior was improved by additional lubrication effect.

In Figure 11-c a modification of the wetting behavior of the FKM took place, emphasizing that oil can penetrate easily in the sealing gap, also reducing wear.

A seal lip grease is a simple method to improve the wetting behavior and will furthermore act as an assembly aid when the seal is installed on the shaft. The grease also protects the seal in conditions where lubrication supply is poor or in startup conditions. Proper selection of the grease is most important to consider the compatibility with the elastomer and with the gear oil. In some applications the grease can also act as an additional sealing mechanism. In most cases seals with dust lips are lubricated at assembly and re-lubrication is not possible. Generally, the quantity of grease required is approximately 40% of the volume between the sealing lip and the dust lip on the seal, distributed evenly around the
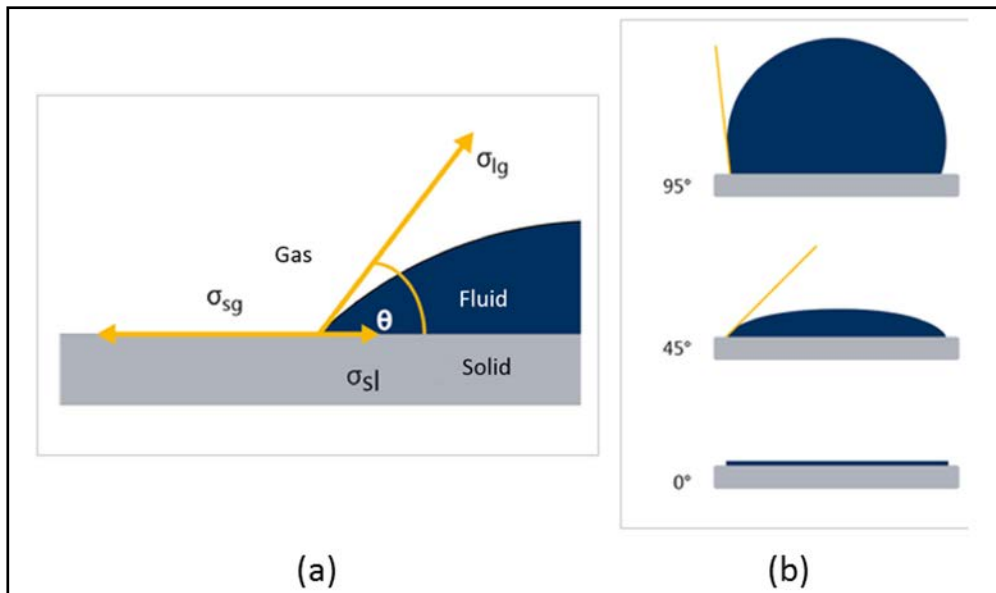

Figure 8 Basic schematic of how to measure the contact angle to evaluate the wetting behavior of elastomer and lubricant.
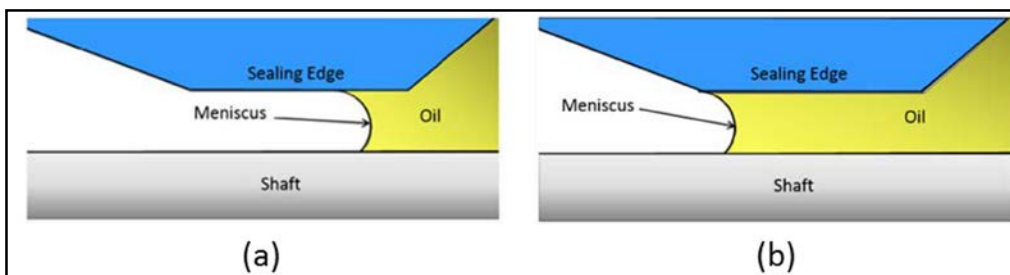

Figure 9 Schematic display of the lubricant penetration under the seal edge: (a) poor wetting behavior; (b) good wetting behavior.

inner circumference. By applying excess grease to the seal, it can falsely appear that the seal is leaking due to the excess oil bleed out of the sealing area.

Chemical interaction. Mechanical properties of elastomers are not only determined by the combination of polymer, filler, plasticizers, and additives, but also through the cross-linking density, which is formed in the vulcanization process. The cross-linking can be altered by chemical interactions.

Possible scenarios are either post-cross-linking, which causes an increase in stiffness/hardness, or a reduction of the cross-linkage through destruction of polymer chains, which results in a reduction of stiffness/hardness (Ref. 7).

The mechanical properties of the elastomer determine the function of the RSS. The sealing edge's ability to follow at excessive shaft eccentricity is defined by the macro mechanical behavior. A change of the mechanical properties of the elastomer, like hardening through a chemical attack, can lead to leakage or cracking within the sealing edge area.

Micro-mechanical properties of the elastomer, such as E modulus and loss modulus, affect the pumping ability and the wear characteristics under the sealing edge. An increase of wear, thus an increase of the sealing edge temperature, can be recognized when the elastomers soften due to chemical interactions with the lubricant. A result may be an acceleration of advanced aging processes. The pumping function can also be altered when the elastomer hardens in the sealing edge area, which may result in leakage or additional wear on the RSS and/or shaft.

Additives — or additive compounds of the lubricant and the temperature in the sealing edge area — define the magnitude of the chemical interaction between lubricant and elastomer.

Sulfur-cured elastomers such as NBR can be chemically altered through EP and AW additives. Typically, EP additives have high sulfur content and can create additional sulfur compounds within the elastomer. AW additives, based on phosphate or zinc compounds, can also alter the sulfur-cured matrix.

Typical FKM compounds, which are bisphenol-cured, can be post-cross-linked through amine compounds — the elastomer eventually hardening.

The speed of chemical reactions is extremely dependent on temperature, which suggests that the most immediate reactions will be close to the sealing edge. Friction — created in the dynamic operation

between RSS sealing edge and shaft — triggers a temperature increase in the sealing edge area. Temperatures up to 50°C are possible compared to the oil sump; thus chemical reactions along the sealing edge area can be accelerated.

A significant change of the mechanical properties in the sealing edge area can have a negative impact on the sealing mechanism, leading to leakage. It therefore becomes crucial to evaluate the changes in the sealing edge area with different lubricants.
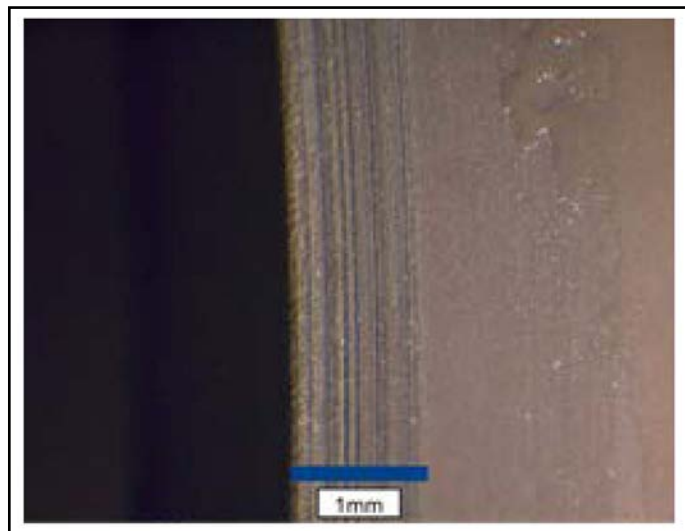

Figure 10   RSS FKM 1 with PG-oil (Viscosity 460) after 1,000h at 110° C (25× magnified) dynamic test.
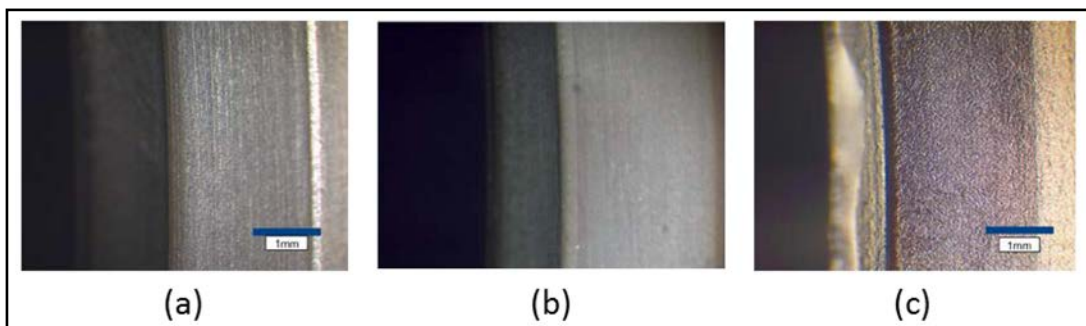

Figure 11   FKM RSS after dynamic long-term testing with PG lubricants: a) optimized FKM compound; b) optimized combination PG oil with additional sealing edge grease; c) FKM RSS with optimized wetting behavior (>1,000 hours).
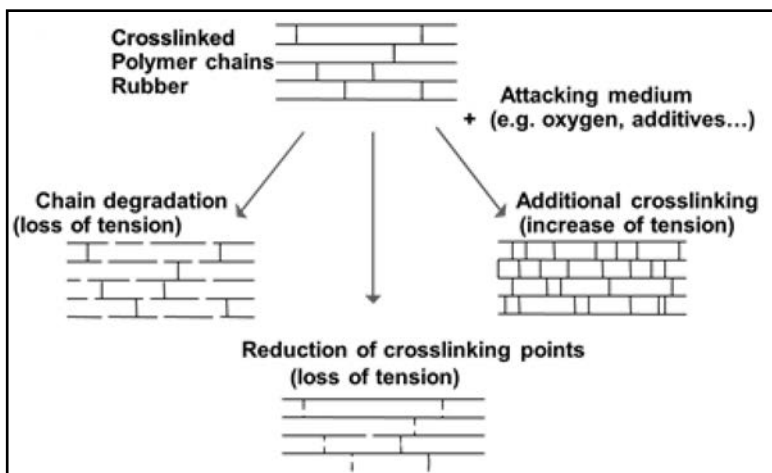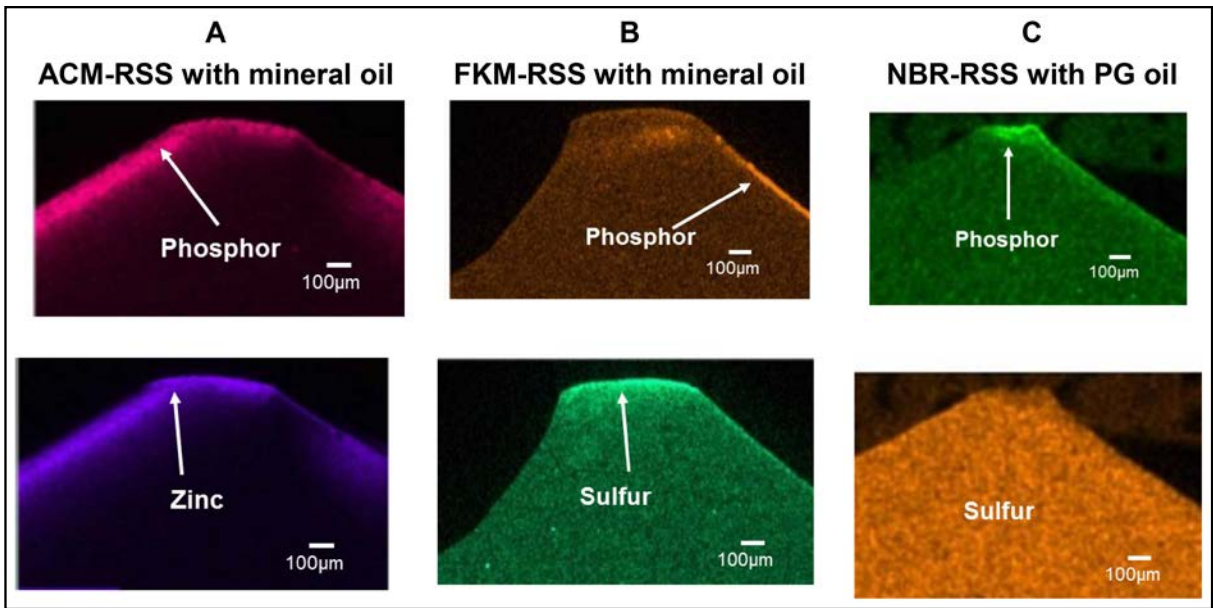

Figure 12   Schematic display of the change of the cross-linking density of elastomers through chemical interaction.

Figure 13   SEM-EDX analysis of an RSS sealing edge cross-section after dynamic long-term tests for different elastomer-lubricant combinations.

Figure 13 displays more intense chemical reactions of lubricants with phosphor, zinc, or sulfur compounds in the sealing edge area.

SEM-EDX analyses of FKM, ACM, and NBR RSS sealing edges are shown (Fig. 13) after thousands of hours of dynamic testing in different oils. One can recognize that different physical and chemical interactions took place in the sealing lip area. There are, dependent on oil composition and RSS compound, different chemical elements on the sealing lip edge. Note that the color of the image is not indicative of the element type; it is simply a color assigned by the software of the SEM-EDX.

Figure 13-a shows a SEM-EDX picture of an ACM RSS sealing edge after 1,000 hours of dynamic testing in mineral oil. One can see that the zinc- and phosphor-rich additives of the lubricant reacted within 200 μm of the elastomer. Axial cracks were visible due to the chemical attack.

Figure 13-b shows an SEM-EDX picture of an FKM RSS sealing edge after 1,000 hours of dynamic testing in mineral oil. One can see the sulfur-rich sealing edge and the phosphor richness in the elastomer matrix. A mechanical change of the sealing edge surface was noted.

Figure 13-c shows a SEM-EDX picture of an NBR RSS sealing edge, after 1,000 hours of dynamic testing in PG oil. This test revealed heavy phosphor enrichment in the sealing edge area. Additionally, sulfur was extracted from the sulfur-cured NBR, which also changes the mechanical properties of the seal.

The question arises—how much did the mechanical
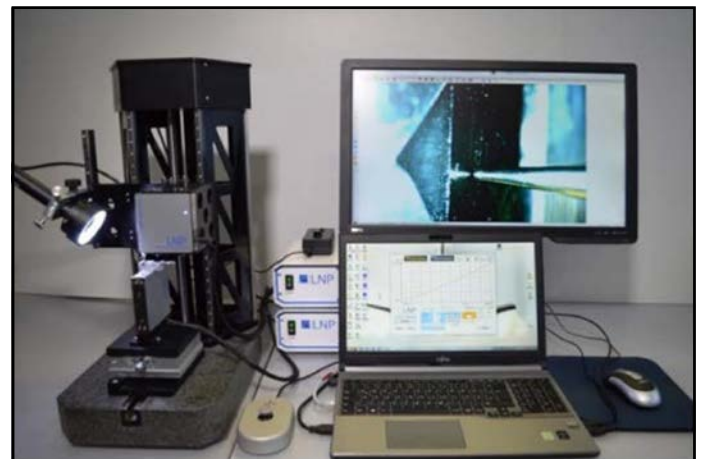
Figure 14   Display of a LNP nano-touch measuring device.
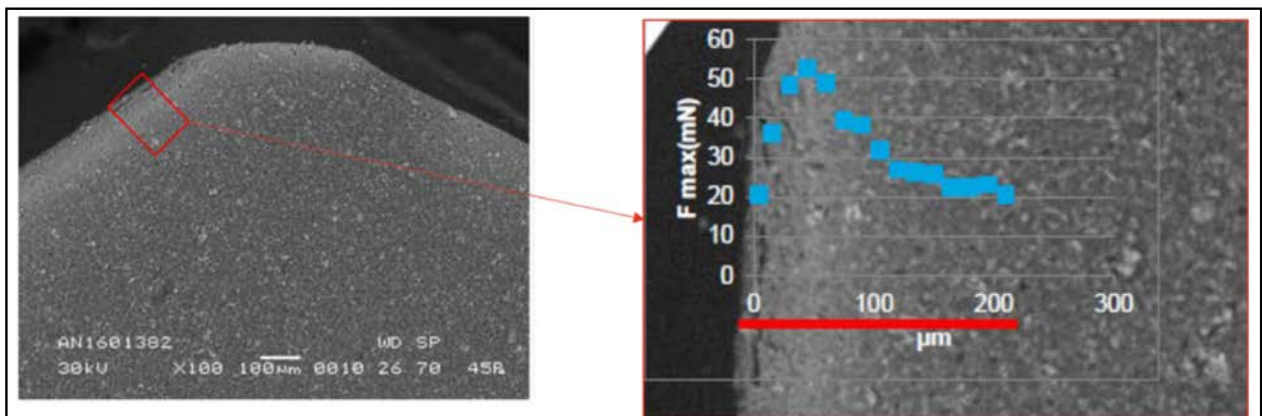
Figure 15   LNP nano-touch measurement.

properties change in the edge area (up to some 100 μm)? To conduct this test, the micro-stiffness of the cross-sections of the sealing edge of the ACM RSS from the edge was measured with an LNP nano-touch device. The LNP measures force with a needle-shaped indenter, which is necessary to enter the material. The measurement can be displayed in μm (Ref. 8).

Figure 15 shows a typical measurement of the macro-mechanical properties in the edge areas of an RSS after long-term dynamic tests. Force (F) is required to insert the nano-indenter through the cross-section.

The stiffness in the edge area has increased, and one can also recognize the concentration of zinc and phosphor in this area. Hence, not only did the micromechanics change, but the result is an altered sealing mechanism through the interaction between the elastomer with the lubricant.

Summary

The development of new test and measurement methods allows the characterization of the physical and chemical interactions between lubricants and RSS.

Shown are complex physical diffusion interactions that can contribute to geometrical changes of the RSS — thus to leakage. On the other hand, the exchange of chemical compounds can also create a chemical transformation within the elastomer, such as post-cross-linking, which will alter the sealing mechanism. Furthermore, the wetting behavior of the lubricant with the elastomer is an important factor for the wear behavior in dynamic applications. The wear resistance can be increased with correct selection of an RSS compound or optimized lubrication system.

The constant design requirements for less friction and reliable sealing function lead to continuous, further development of the tribological system consisting of seal materials, the sealing lip design, and lubricant. To achieve the best RSS-lubricant lifetime solution, both components must be adapted to the applicable application. Therefore, it is necessary to have a deep knowledge of the materials — on both the lubricant and elastomer side. An evaluation of the interactions is possible through the usage of various static and dynamic lab methods, as well as the usage of complex analysis methods. The gathered knowledge guarantees long-term sustainability for the application. **PTE**

References

1. Stakenborg, M.J.L. *Tribology International*, Vol. 21, No 6, 1988, p. 335.
2. Buhl, S. and W. Hasse. Antriebstechnik, Vol. 4, 2006, 76.
3. Winkenbach, R., E. von Arndt and H. Mindermann. "Interactions Between Sealing Materials and Lubricating Oil Additives," SAE Technical Paper 870509, 1987, DOI: 10.4271/870509.
4. Starmer, Philip H. and C. H. Lufter. "Swelling Effect of Liquids on NBR (Nitrile Rubber)," Rubber Chemistry and Technology, July 1961, Vol. 34, No. 3, pp. 964–974.
5. Kusch, P. *LCGC North America* Vol 31, 2013, p. 248.
6. Konar, J. and S. Kole. *Polymer*, Vol 61, 1996, p. 501.
7. Santoso, M.A. PhD dissertation, University of Hannover, 2011.
8. Reiners, K. *KGK*, Vol. 67, 2014, p. 18.

Dr.- Ing. Matthias Adler has held a number of positions thus far in his career, including (2001-2010) material development for polyurethane and fuel cell sealings; (2010-2015) senior chemist (rubber-lubricant-interaction, fuel cell sealing); and, since 2015, head of global material development at the Oil Seal Division Industry.

Joseph Walker is the global technology director of materials and laboratories for Freudenberg Sealing Technologies. In this position he is globally responsible for overseeing all advanced materials technology development and management of the FNST/FST laboratories. He is also the regional NAFTA leader for chemical regulatory compliance for FNST. He is located in the Plymouth, MI, corporate R&D headquarters of Freudenberg-NOK Sealing Technologies. Prior to joining Freudenberg, Walker served as silicone rubber business team leader for Wacker Silicones Corp. There, he was responsible for research, development, and sales and marketing. Previously, he was an engineering fellow for Alliant Techsystems (formally Honeywell Defense and Marine Systems), where he focused on material design, processing and application for various U.S. Department of Defense programs. Walker has also held positions at Stauffer Chemical, Phillips Petroleum and Firestone Tire & Rubber Co. He was the 2012 chairman of the American Chemical Society, Rubber Division, a member of the Rubber Industry Advisory Board for Ferris State University, board member of the Association of Rubber Product Manufacturers and is past-chair and board member of the Detroit Rubber Group. Additionally, he is a member of Society of Automotive Engineers, Society of Plastics Engineers, Original Equipment Suppliers Association, Automotive Industry Action Group, and the Americas Tech Team of the American Chemistry Council. A graduate of Lawrence Technological University, he holds more than 20 patents in the fields of materials applications and compositional chemistries. He currently holds more than 20 patents and has authored and edited various chapters in text and industry publications.

Craig Desrochers, P.E. tribologist, Klüber Lubrication NA LP, graduated from Western New England University with a bachelor's degree in mechanical engineering and obtained his professional engineering license in 2013. He has been an application and service engineer at Klüber Lubrication for four years and has recently assumed the tribologist role, in charge of the mechanical testing lab at Klüber Lubrication's North American headquarters in Londonderry, New Hampshire. His primary focus at Klüber as an application engineer was on the gear oil and gear grease product lines, with a focus on OEM relations. Prior to joining Klüber Lubrication, he worked as a mechanical engineer on nuclear powered submarines at Portsmouth Naval Shipyard primarily focusing on the maintenance, testing, and modernization of the steam propulsion turbines, lubrication systems, and main reduction gearing systems. Desrochers is an active AGMA member and continues to focus on the gear oil industry.

Matthias Pfadt M. Sc. has since 2015 been a manager for application engineering at Klüber Lubrication München. He received his master's degree in mechanical engineering from TU München in 2015. Since 2016, Pfadt has been investigating lubricant elastomer interactions in gear applications.

Sascha Grasshoff