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µ-Mechanical characterization of tribologically stressed elastomer surfaces with respect to radial shaft sealing systems

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This paper introduces the new µ-mechanical characterization method and its application for the post-test analysis of radial shaft seals (RSS) used for dynamic lubricant-elastomer compatibility tests. Therefore, the measurement procedure and accuracy will be discussed as well as the features which can be drawn from the measured force-displacement curve. Furthermore, it will be shown, how these features allow a precise evaluation of the seal material condition regarding hard deposits, hardening and softening. This will be summarized by showing the correlation of the visual-haptic elastomer assessment and the results of the newly developed characterization method which will increase the significance of dynamic lubricant-elastomer tests.

1 Introduction

The radial shaft seal (RSS) is a widely used machine element, e.g. in gearboxes to seal lubricants against the environment. For this purpose, the RSS, the shaft surface, and the sealed fluid as well as the operation conditions (sliding speed, temperature, pressure, etc.) form a tribological system - the radial shaft sealing system (Figure 2). In terms of sustainability and cost efficiency, high expectations are set on the reliability and service life of such radial shaft sealing systems.

Figure 1 Worm-gearbox with leakage due to lubricant-elastomer incompatibility

Therefore, downtimes due to maintenance or even leakages (Figure 1) must be avoided. In particular, the complex interactions between the sealed lubricant and the radial shaft seal have a major influence on the long-term reliability and lifetime of a radial shaft sealing system. It is therefore essential to ensure lubricant-elastomer compatibility under dynamic tribological stress.

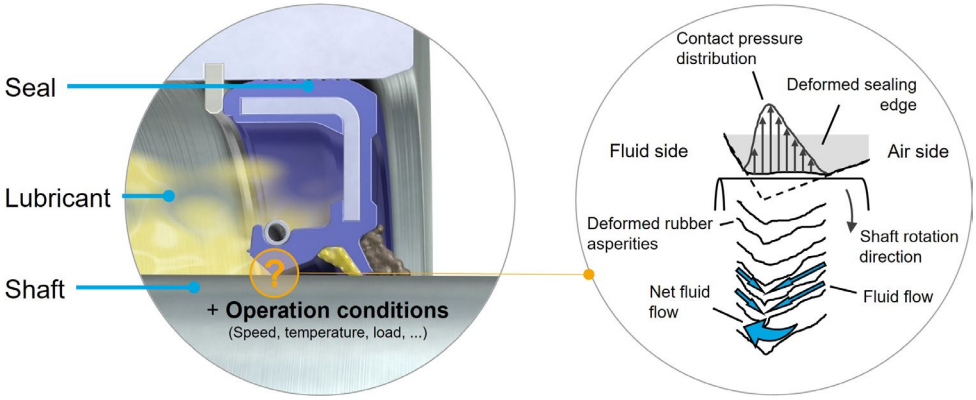

Figure 2 Radial-shaft-sealing System [1] (left side) and reverse pumping effect according to Kammüller [2] (right side)

The lubricant elastomer compatibility can be verified by dynamic tests in accordance with established industry test standards. Due to the tribological stress of the lubricant and seal material within the sealing gap, physical and chemical interactions between lubricant and elastomer take place (see Figure 3) [5].

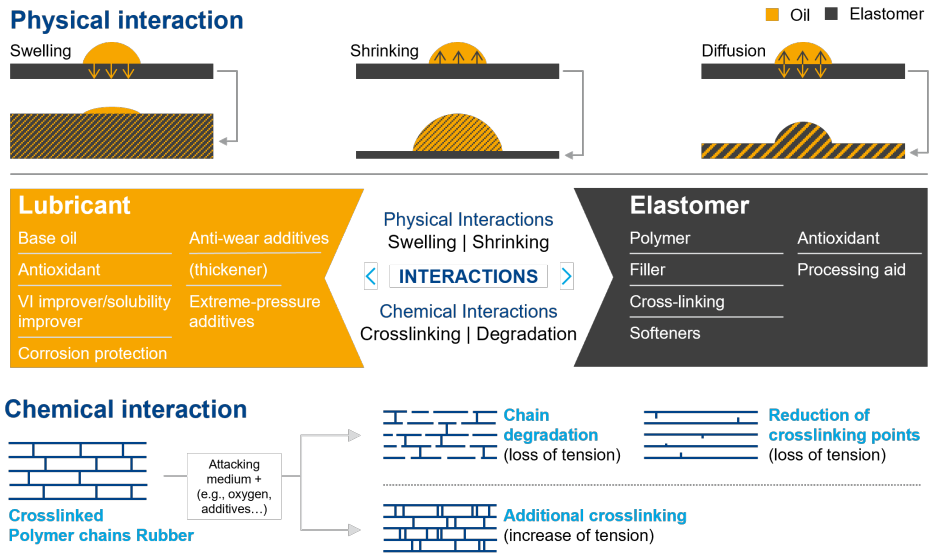

Figure 3 Lubricant-elastomer interaction

Depending on whether the compatibility between lubricant and elastomer is given or not the intensity of interactions is different and has impact on the properties of the lubricant and elastomer. Especially the near surface material properties (µ-mechanical material properties) within the first 60 µm of the sealing edge are crucial for a

well performing reverse pumping effect (see Figure 2, right side) and therefore the performance of the radial shaft sealing system.

2 RSS Analysis and Characteristics

The post-test analysis of the RSS is an essential process to determine the material condition and how the lubricant affects the seal under tribological stress. Besides leakage, seal wear width, shaft wear depth, radial load- and interference change it is of great importance to consider the near surface material condition of the sealing edge. While the seal and shaft wear, the radial load and interference are measurable continuous values the seal material condition, is rated based on visual-haptic feedback of the material by seal experts with years of practical experience. The material condition rating scale is not a continuous value but a categorial with five levels: without (= 1), little (= 2), moderate (= 3), heavy (= 4) and severe (= 5). This scale is applied to nine post-test seal characteristics to determine the intensity of the seal condition change, see Table 1.

Table 1 Post-test seal condition characteristics

Characteristic	Method
Grooving	Visual
Hollow wear	Visual
Contact discoloration	Visual
Cracking	Visual*
Blistering	Visual*
Soft deposits	Visual-haptic
Hard deposits	Visual-haptic
Hardening	Visual-haptic
Softening	Visual-haptic

*) in some cases, also haptic feedback

While grooving, hollow wear and the wear band width, are describing the geometrical change of the sealing lip, the other characteristics, such as deposits (soft and hard), cracking, blistering, hardening, and softening allow a conclusion regarding the physical and chemical interaction influencing the seal material properties [4].

Even though that all characteristics are important to be considered, hard deposits, hardening and softening are essential for the dynamic sealing function and at the same time the most difficult to rate. Because all three characteristics are evaluated not only through visual inspection, but also by haptic feedback, which indicates whether the sealing edge is harder or softer than before the test or if there is a hard, brittle layer covering the sealing edge.

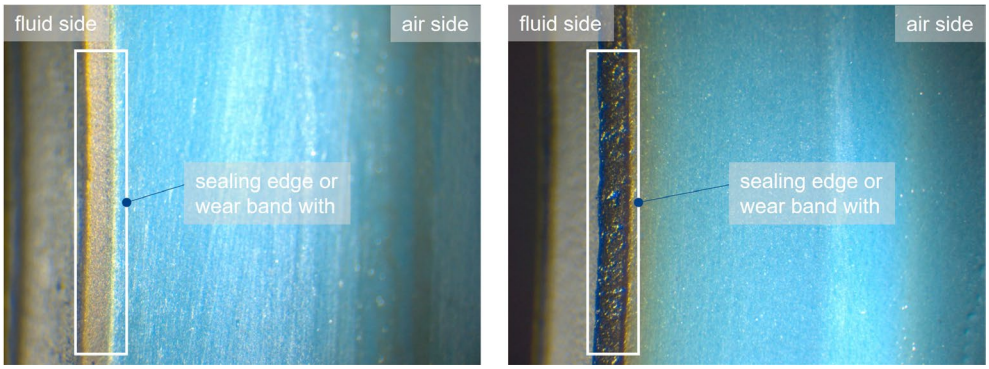

Figure 4 NBR seal after 768h dynamic test showing no damage (test no. 3, left side) and hard deposits covering the sealing edge due to incompatibility (test no. 2, right side)

The left side of Figure 4 shows a post-test sealing edge of a NBR seal without any sign of a significant change of the material property, indicating a good lubricant elastomer compatibility. All other results of the dynamic test have been within the limits too. In comparison, the sealing edge in Figure 4 on the right side is covered by a dark, brittle, hard layer – hard deposits – indication a lubricant incompatibility. The corresponding dynamic test results show that 3 out of 3 seals leaked after only 120 h and the shaft wear is above 10 µm.

This comparison uses two extreme examples – highly compatible (Figure 4, left side) vs. highly incompatible (Figure 4, right side) lubricants which makes it easy to differentiate one from the other. However, for the purpose of development and approval tests, it is crucial to distinguish the condition of the seal material across a range of possibilities, ensuring repeatability and reproducibility even within these extreme variations. Therefore, it is necessary to move from a visual-haptic feedback rating with a categorial scale to an objective measurement method of continuous values.

3 µ-Mechanical Material Characterization of RSS

The new tactile seal characterization method – “µ-mechanical seal characterization” – is realized by using a micro indentation tester named “LNP® nano touch” with a high precision force-displacement sensor (force resolution: 0.6 mN). Due to the very small probe tip radius of R = 40 µm it is possible to measure directly on the wear band, even of narrow wear band widths of 100 - 150 µm (see Figure 5, detailed view).

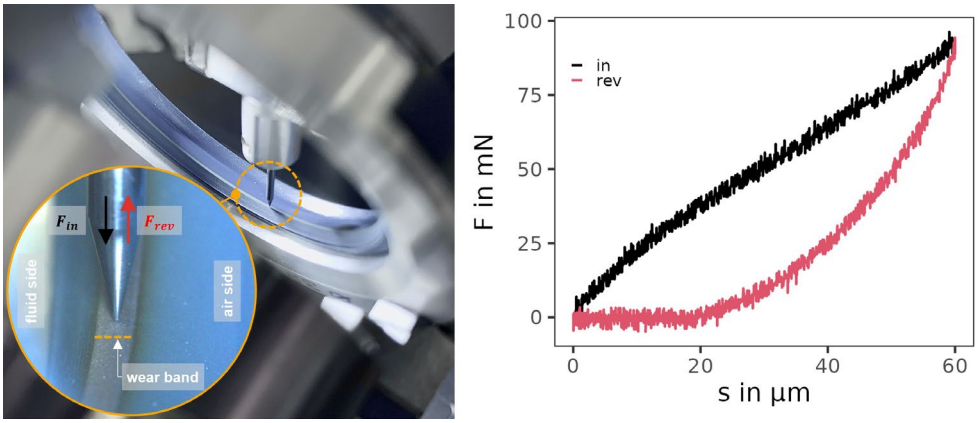

Figure 5 µ-Mechanical measurement setup and force-displacement curve

In Figure 5 (left side) is shown the measurement setup with the mounted seal and a detailed view of the probe tip positioned on top of the wear band. The measurement results in a force-displacement curve (Figure 5, right side) showing the force F on the vertical axis in mN and the penetration depth s on the horizontal axis in µm. The colour differentiates the force when the probe is penetrating the seal F_{in} (black line) and reversing F_{rev} (red line). To ensure comparability of the results it is necessary to use the same measurement parameters (see Table 2).

Table 2 Measurement parameters

Measurement	Value	Unit
Probe-tip type	Sphere (Radius)	-
Probe-tip radius	40	µm
s_M	60	µm
v_M	5	µm/s
t_M	0	s
s_L	0	s
v_L	5	µm/s
t_L	0	s
Type	v-Control Linear	-

However, with the force-displacement curve alone it is not possible to characterize a seal properly. Thus, features need to be calculated from the curve which then allow the characterization of the seal material properties, in particular: hard deposits, hardening and softening.

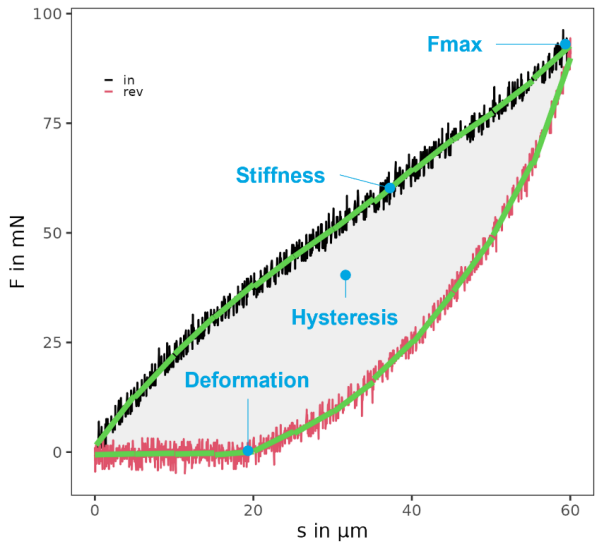

Figure 6 µ-Mechanical characteristics calculated from the force-displacement curve

Figure 6 shows qualitatively the calculated features from the force-displacement curve in blue. F_{max} is the maximum measured force at the maximum penetration depth s_M. The Hysteresis H is the relative area enclosed by the F_{in}- and F_{rev}-curve related to the area under the F_{in}-curve. The slope derived from a linear regression of the force-displacement curve at a discretization length of 5 µm corresponds to the stiffness S of the seal material. Another interesting feature is the homogeneity b which describes the rate between the surface stiffness and the bulk stiffness. The surface stiffness is considered as the mean stiffness of the penetration depth range from 0 to 15 µm and the bulk stiffness as the mean stiffness from 50 to 60 µm. Table 3 summarizes the most important features calculated from the force-displacement curve for a proper post-test µ-mechanical seal material characterization.

Table 3 µ-Mechanical features for seal characterization

Characteristic		Unit
F_{max}	Maximum force	mN
H	Hysteresis	-
S	Stiffness	mN/µm
b	Homogeneity	-

4 RSS Characterization Map and Interpretation

Finally, Figure 7 shows the RSS Characterization Map including the maximum force F_{max} in mN on the horizontal axis, the hysteresis H in % on the vertical axis and the homogeneity b as colour code.

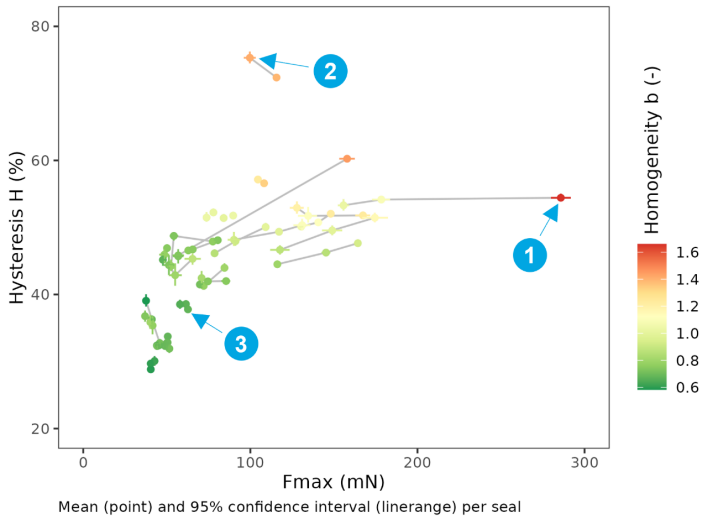

Figure 7 RSS Characterization Map

The Characterization Map includes only results from dynamic tests with seals out of 72 NBR 902, but with different test conditions (e.g. fluid, pressure, duration, sliding speed, etc.). The two examples, test no. 2 and 3, were tested at the same test conditions but with different fluids and test no. 1 additionally at a higher duration time and pressurization. The general trend in data shows with increasing maximal force F_{max} a fast rise of the hysteresis H and the homogeneity b (green to red) before it is levelling out at high F_{max} values. This curve progression correlates with the seal material degradation intensity due to lubricant elastomer incompatibility.

Table 4 shows the post-test material condition rating results of the visual-haptic feedback method and the corresponding results from the micro mechanical characterization.

Table 4 Post-test material condition rating results

No	Damage	Rating (-)	Fmax (mN)	Hysteresis (%)	Stiffness bulk (mN/µm)	Homogeneity (-)
1	Hardening	5	280	54	3.0	1.7
2	Hard deposits Softening	5 4	99	78	1.6	1.3
3	none	1	61	38	0.9	0.7

The test results clearly show the difference between hardening and hard deposits. Since hardening is mainly correlated to high F_{max} values and a bulk stiffness S greater than approx. 1.8 mN/µm while hard deposits correlate with a high hysteresis H, homogeneity b greater than 1.1 and relatively small F_{max} values. Often the seal material underneath hard deposits is softened as well. In Figure 8 the seal condition and stiffness curves of test 1 to 3 are shown.

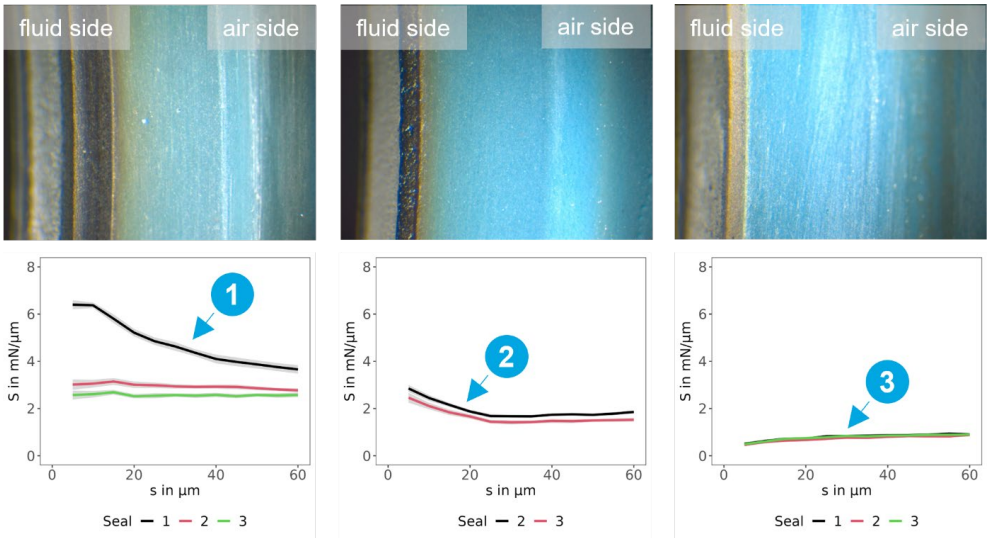

Figure 8 Seal wear band and stiffness curve

Seal 2 and 3 of test 1 show a typical stiffness curve for hardened seals, a constant progression at a high stiffness level (bulk stiffness approx. 3 mN/µm). Sometimes the material at the surface is even more hardened as the stiffness curve of seal 1 reveals. However, the stiffness curve of seals with hard deposits show a significant drop to a lower level of stiffness (bulk stiffness approx. 1.6 mN/µm) after the first 15-20 µm. The penetration depth range where the stiffness is degreasing until it is levelling out corresponds to the layer thickness of the hard deposits. In contrast the stiffness curves of test 3 are slowly rising with increasing penetration depth s and levelling out at a bulk stiffness of approximately 1 mN/µm indicating that no material degradation took place and therefore a good lubricant elastomer compatibility.

5 Summary and Conclusion

The new µ-mechanical seal characterization method realized by using the micro indentation tester from LNP® and the here presented features drawn from the force-displacement curve, are the basis to successively update the state-of-the-art visual-haptic seal assessment method. Features such as the maximum force F_{max}, hysteresis H, homogeneity b and the stiffness curve S allow a characterization of the seal

material properties change and thus an evaluation of the lubricant elastomer compatibility. This characterization and evaluation are based on highly precise measurements which will increase the significance of dynamic lubricant elastomer compatibility tests even more. Other interesting outcomes of this analysis are, that it shows:

1. The new µ-mechanical characterization method accurately reflects the results from the visual-haptic feedback method and the dynamic test results.
2. With increasing seal material degradation due to incompatibility, the precise µ-mechanical measurement shows an increased, up to 4 times higher, variation of the results. This suggests that the variation is mainly caused by unstable tribological conditions within the contact due to an incompatibility.

Increasing the experience with the new µ-mechanical characterization method will allow to narrow down the exact feature combinations and limits for a complete characterization. Also, the development of further features [3] will provide the possibility to characterize additional characteristics e.g. in terms of seal wear or permanent deformation. Furthermore, it is necessary to extend the analysis to other elastomer compounds such as FKM's, ACM's and HNBR's.

6 Nomenclature

Variable	***Description***	***Unit***
F	Measured force	[mN]
F_{max}	Maximum force	[mN]
H	Hysteresis	[-]
S	Stiffness	[mN/µm]
b	Homogeneity	[-]
s	Penetration depth	[µm]
s_M	Maximum penetration depth	[µm]
v_M	Penetration velocity	[µm/s]
t_M	Holding time at maximum penetration depth	[s]
s_L	End of test penetration depth	[µm]
v_L	Reverse velocity	[µm/s]
t_L	Holding time at end of test penetration depth	[s]

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