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Advanced characterization of sealing counter surfaces in linear applications

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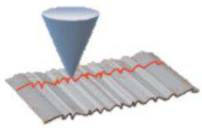
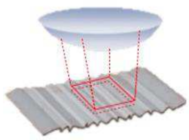
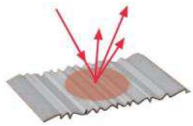
Counter surfaces are an important aspect for every sealing application and have a direct influence on the sealing performance of the system. Historically, the counter surface is described with multiple roughness parameters based on 2D profile or 3D topography measurements. In addition to the standard parameters, light scattering can be used to describe the counter surface. Compared to the common profile roughness parameters, light scattering measures the angle distribution of a profile and is therefore more robust against external influences. In addition, light scattering measurements are faster at characterizing a complete running surface. In this study, the effect of one rod seal geometry made from PTFE and PU materials on the surface characteristics of the rod is investigated. A deeper understanding of the tribological system is achieved by analyzing for the first time the light scattering roughness parameters of a tested rod surface in addition to the standard profile roughness parameters.

1 Introduction

A linear rod sealing system is a tribological system with the seal and the rod as the tribological surfaces and the hydraulic fluid as intermediate media. The friction and wear of tribological systems is greatly influenced by the surface roughness characteristics of the rod or counter surface of the seal. Classical surface roughness parameters are determined from a surface profile or topography which is measured mechanically via the tactile sectioning method or optical profilometry, e.g. interferometry or confocal microscopy as shown in Figure 1. The tactile method falls under the contact-based measurement techniques, while the optical measurement methods are non-contact measurements. Roughness parameters based on the surface trace acquired by these types of methods are described in DIN EN ISO 21920-2:2022-12.

An alternative to conventional measurement methods is the non-contact optical measurement methods based on scattered light described in VDA2009 [1]. In contrast to classical roughness parameters, which are based on the roughness profile, light scattering parameters are based on the reflectance properties of the rough surface. In previous studies, light scattering has been adopted to analyze roughness and shaft lead effects in rotary sealing systems [2] [3]. No previous work is known on the influence of light scattering parameters in linear sealing systems. Especially for linear sealing systems, where tactile measurements are often restricted to only a small portion of the rod surface, light scattering measurements are hypothesized to offer a considerable advantage in terms of cost and efficiency of characterizing the complete rod surface. For the first time, this research demonstrates the use of light scattering methods for the characterization of the surface roughness of the rod in hydraulic sealing systems.

Table 1: Comparison of different surface measurement methods

		
Stylus method	Confocal microscopy	Angle-resolved scattered light measurement technology
Profile parameters: Ra, Rz, Rk, etc.	Surface parameters: Sa, Sz, Sk, etc.	Scattered light parameters: Aq, Aqm, Aqmax, etc.

2 Scattered light measurement

2.1 Roughness parameters

The scattered light parameters capture both the roughness and the reflectance of finely processed surfaces by measuring the distribution curve of the scattered light.

The following study focuses on the parameter Aq, which denotes the variance of the scattered light distribution. Aq describes the second statistical moment of the angular distribution and is an integral measure for the micro-geometry or the extent of roughness within the light spot, respectively [1].

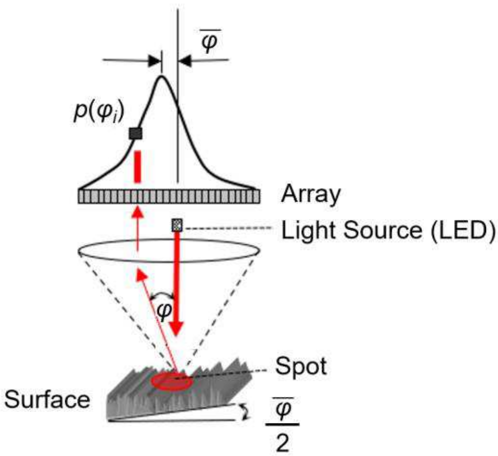


Figure 1: Principle of the angle-resolved scattered light measurement

$$\text{Aq} = k \sum_{i=1}^{n} (\varphi_i - \overline{\varphi})^2 \, p(\varphi_i) \tag{1}$$

In Equation (1), k is a normalization factor, φ is the scattering angle, $p(\varphi)$ is the normalized intensity distribution, n is the total number of angle classes, and the bar denotes an average value.

Aq is corresponding to the second statistical moment of the surface power spectrum and reacts very sensitively to changes in surface properties. It is directly proportional to the ISO21920 parameter Rdq [4] and is traceable according to ISO17025 [5]. Its contact mechanical significance is emphasized by Popov [6].

2.2 Sensor principle

In the current study, the Optosurf OS500 scattered light system was used. The measurement spot on the surface is generated by an illumination beam path which, depending on the design, projects measurement spots of various sizes onto the surface. The light scattered back from the surface is transmitted onto a linear detector array by means of Fourier optics. This array converts the incident intensity distribution into electrical currents, which are then digitized and passed on to a microprocessor for further processing. For the standard sensor, the captured angular range is 32°. The scattered light optics are angle-corrected, achieving insensitivity to distance variations. The measurement distance can vary by up to +/- 1 mm for flat samples without changing the distribution curve and thus the roughness characteristic Aq [7]. A full description of the transfer function given by Seewig [8].

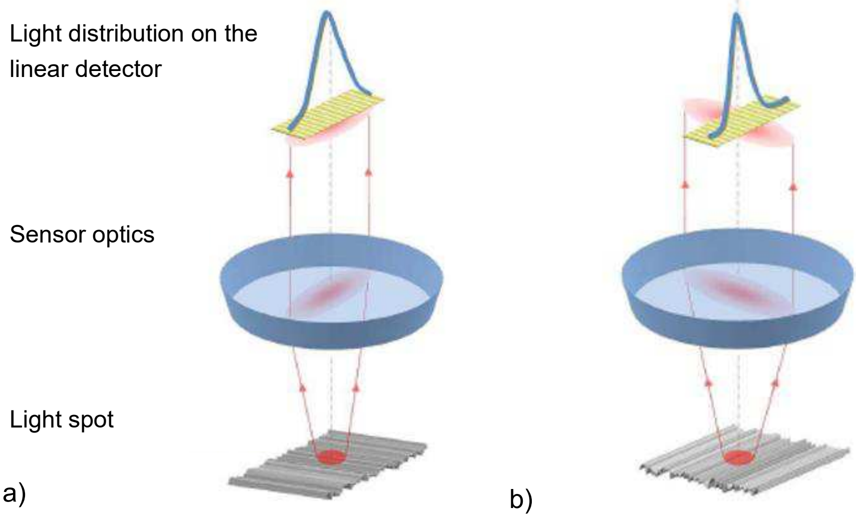


Figure 2: a) Crosswise roughness measurement per definition: diode array oriented across machining direction; b) Longwise roughness measurement per definition: diode array oriented parallel to the machining direction

Depending on the orientation of the sensor or the surface, the roughness is measured transverse to the machining grooves or parallel to them, as illustrated in Figure 2. By default, the two measurement directions are defined as follows:

- Crosswise roughness measurement: diode array oriented across (perpendicular) machining direction.
- Longwise roughness measurement: diode array oriented parallel to the machining direction.

In the following study, the two sensor orientations are defined as

- Crosswise roughness measurement: perpendicular to rod moving direction
- Longwise roughness measurement: perpendicular to processing direction

3 Test rig and test procedure

The linear rod test rig is equipped with two equal test cells arranged symmetrically, see Figure 3. Each hydraulic cylinder is driven linearly by a drive motor via a deflection pulley. The resulting position time signal can be approximated as a sinus. Due to the conversion of the circular to linear movement the speed is not constant. Due to inconstant speed over movement the seal experiences different friction states like static friction, mixed friction and hydrodynamic friction. A test chamber is installed on each test rod. Each test chamber is each equipped with two rod seals in a face-to-face arrangement.

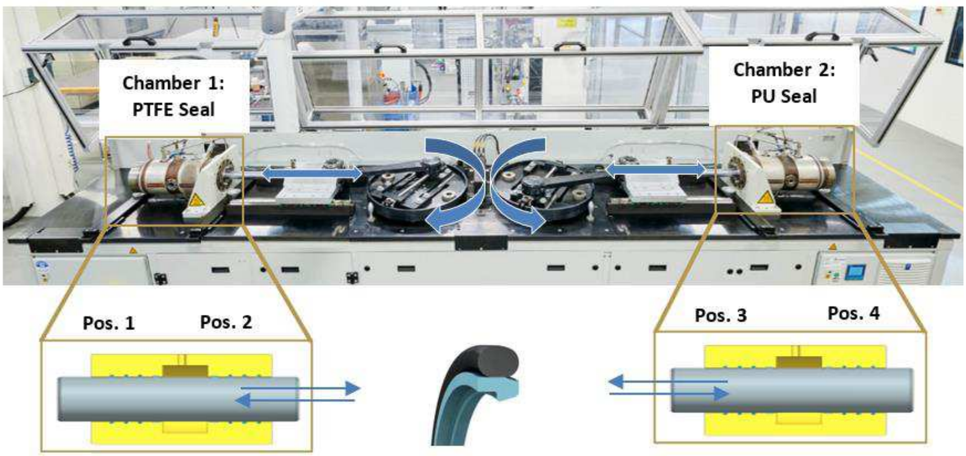


Figure 3: Linear rod test rig

The tested seal configuration consists of a Stepseal® 2K with an O-Ring acting as an energizer. The seal materials used are PTFE (T46) and PU (Z53). T46 is a bronze-filled PTFE, while Z53 is a polyurethane (PU) material. The test was conducted using HLP 46 hydraulic oil as the lubricant. The operating conditions included a constant pressure of 400 bar, an oil temperature of 60 °C, an average rod velocity of 0.2 m/s, and a total number of 600,000 rod double strokes.

4 Test results

4.1 Tactile roughness measurement

The tactile roughness measurement was carried out with the Hommel Etamic T8000 device. The mean Rz values before and after the test are shown in Figure 4. The initial quality of counter surface is measured at three locations along the rod. The initial value in terms of Rz is around 0.6 µm.

After the test the counter surface is measured at twelve locations. As shown in Figure 4 the mean Rz value after the test is similar to the value before the test. As a conclusion, the change of the widely used Rz is not indicating a change of the counter surface during the test. In addition, the Average Aq (Aqm) was estimated based on the running area. It already shows the bigger change of the Aqm. In the following chapter the Aq will be explained in detail and in addition the distribution over the surface.

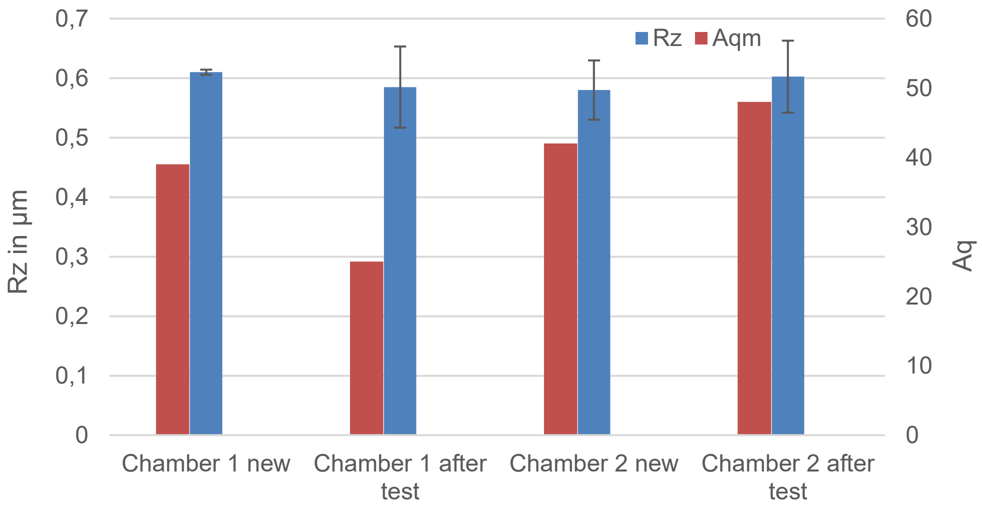


Figure 4: tactile and scattered light measurement before and after test; chamber 1 and chamber 2

4.2 Scattered light analysis before test

As stated above, Aq [1] is seen as a supplementary value to describe the surface roughness. For the conducted tests, new rods were used for each measurement. They were measured using the scattered light sensor before and after the test. Each measurement was performed with the sensor oriented crosswise (i.e. perpendicular to the rod movement) and longwise (i.e. perpendicular to the processing direction). Figure 5 shows a scan of the entire lateral surface of rod 1 before the test with the sensor oriented crosswise. Figure 5 reveals a uniform distribution of Aq. The Aq mean value in the crosswise direction is 5.57 and the Aqmax [1] value is 18.26.

The measurement with the sensor orientation longwise clearly reveals the machining traces, Figure 6. A possible last polishing step could be feed marks of centerless grinding. The Aq mean value in the longwise direction is 45.75, and the Aqmax value is 66.20.

Exemplary, only the scans of rod 1 were depicted, as rod 2 shows a similar image. For rod 2, the Aq mean (Aqm) value in the crosswise direction is 5.56, and Aqmax is 20.37. The Aq mean value in the longwise direction is 45.25, and Aqmax is 68.33.

Table 2: statistic to chamber 1, new; sensor orientation perpendicular to rod moving direction

Aqm	5.57
Aqmax	18.26
Aqs	0.76

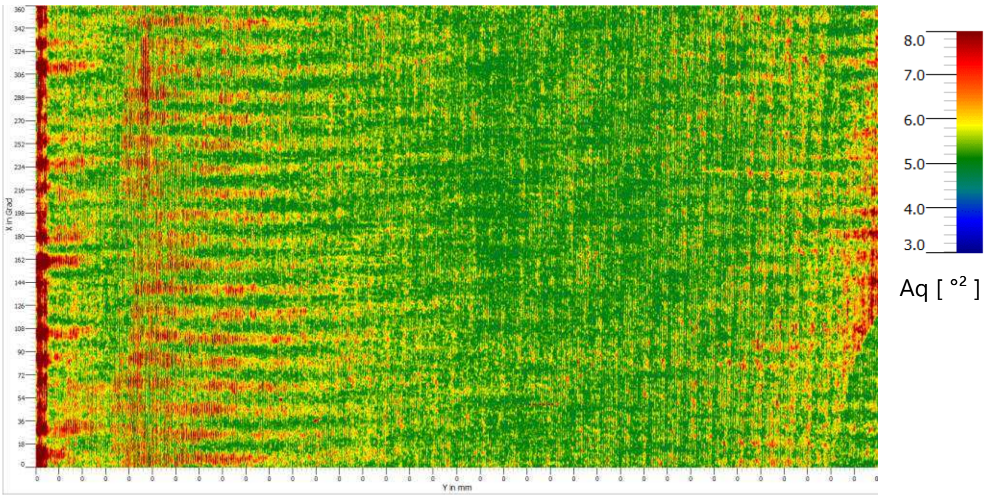


Figure 5: Aq, chamber 1, new; sensor orientation perpendicular to rod moving direction

Table 3: statistics chamber 1, new; sensor orientation perpendicular to processing direction

Aqm	45.75
Aqmax	66.20
Aqs	3.31

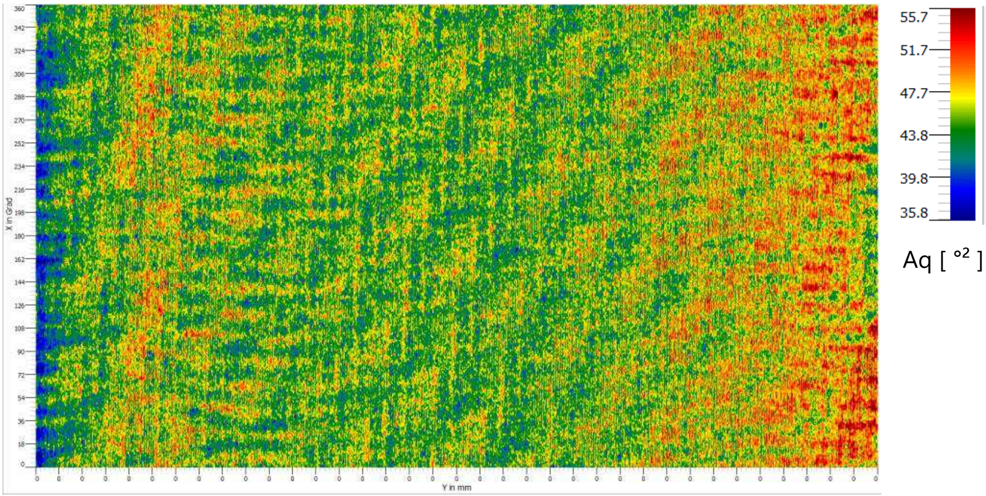


Figure 6: Aq, chamber 1, new; sensor orientation perpendicular to processing direction

4.3 Scattered light analysis after test

The following Figure 7 shows the Aq distribution after testing on rod 1. In the running areas at positions 1 and 2 marked as region 1 and region 2, the Aq values have partially increased from 5.57 to 9. This indicates surface roughening. The measurement with the sensor oriented crosswise (perpendicular to the machining direction) clearly reveals the running tracks of the seals. In the red areas equate with higher Aq values, grooves are visible in the running direction.

Table 4: statistics chamber 1, PTFE, after test; sensor orientation perpendicular

Aqm	6.35
Aqmax	16.41
Aqs	0.89

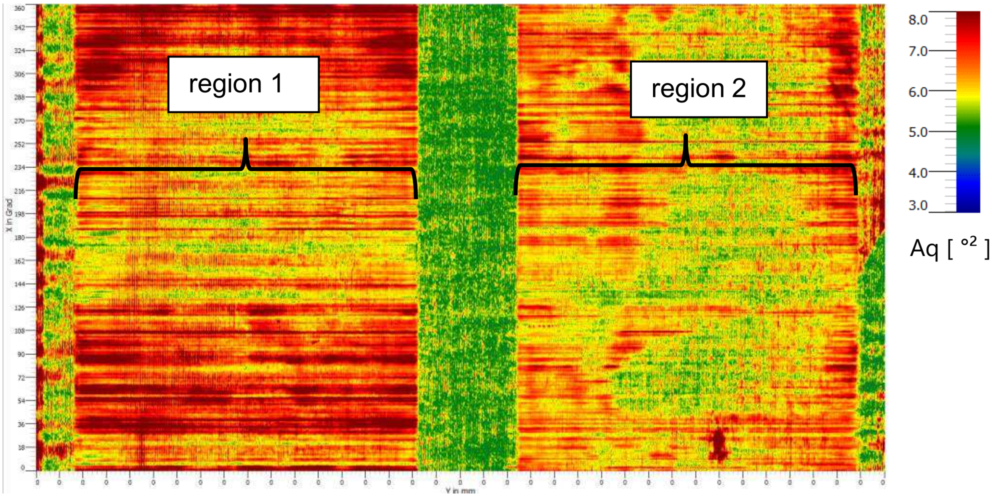


Figure 7: Aq, chamber 1, PTFE, after test; sensor orientation perpendicular to rod moving direction

Figure 8 illustrates the examination of the rod surface of rod 1 (PTFE) with a sensor alignment in the longwise direction. The figure can be divided into five regions. Regions 1 and 2 denote the section of the seal's running surface. Here it is evident that the influence of the seal overlays the machining marks. The machining marks are visible in the unworn area (region 4) at an Aq value of approximately 40 (orange areas). In regions 1 and 2, significant smoothing of the rod surface is observed within the seal's running areas. The Aq values decrease to between 30 and 20 in region 5. Further reduction in Aq values occurs in region 3. These areas correspond to the reversal points in the seal's motion cycle. These regions belong to the upper and lower dead points, where the velocity drops to zero. Lubrication ceases, and the seal comes into direct contact with the opposing surface, resulting in localized surface smoothing. As the velocity increases, the seal enters the hydrodynamic regime and is well-lubricated again. Due to this lubrication state, region 5 exhibits less surface smoothing.

Table 5: statistics chamber 1, PTFE, after test; sensor orientation perpendicular to processing direction

Aqm	28.84
Aqmax	59.51
Aqs	10.43

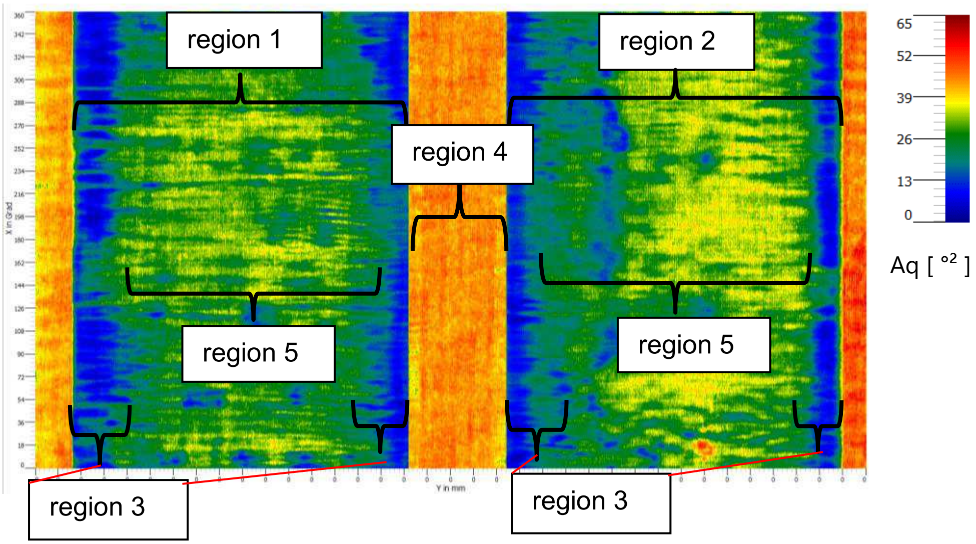


Figure 8: Aq, chamber 1, PTFE, after test; sensor orientation perpendicular to processing direction

Table 6: statistics chamber 2, PU, after test; sensor orientation perpendicular

Aqm	5.66
Aqmax	17.52
Aqs	0.79

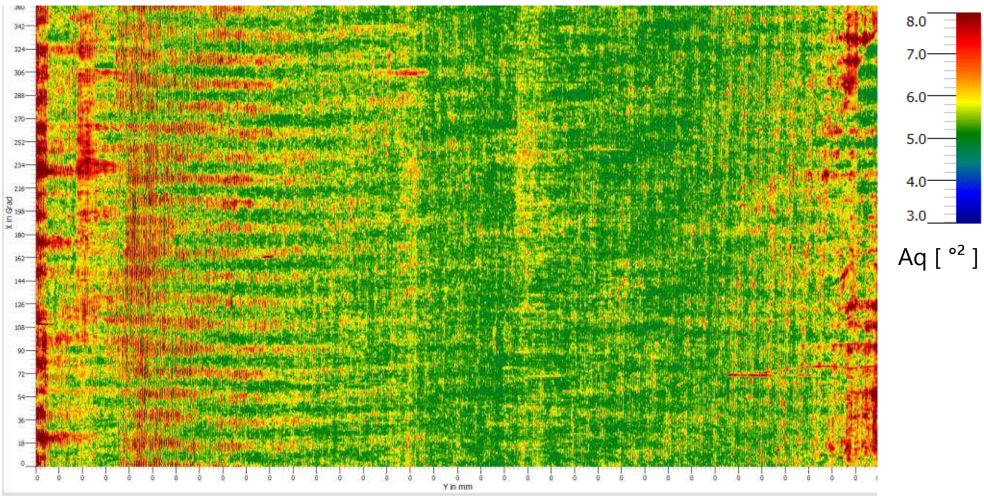


Figure 9: Aq, chamber 2, PU, after test; sensor orientation perpendicular to rod moving direction

Table 7: statistics chamber 2, PU, after test; sensor orientation perpendicular

Aqm	44.98
Aqmax	74.80
Aqs	3.40

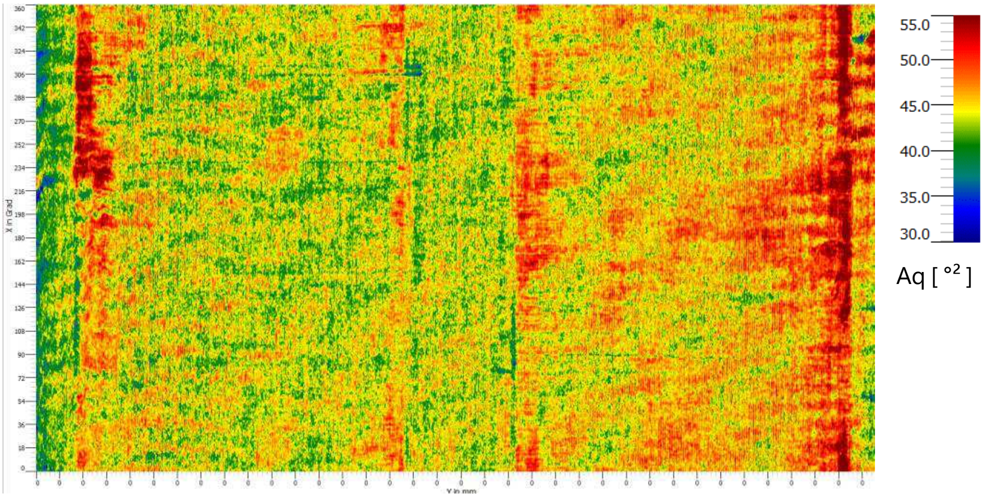


Figure 10: Aq, chamber 2, PU, after test; sensor orientation perpendicular to processing direction

It should be noted that for the evaluation of chamber 1 a scaling of the Aq value over a larger range was used, because PTFE has a stronger impact on the rod surface than PU, refer to region 3 in Figure 8. Aqs corresponds to the standard deviation of the measured values and is 10.55 for rod 1 (PTFE) and 3.4 for rod 2.

The PU seal has significantly less impact on the rod surface. As shown in Figure 9, there are minimal changes in the surface.

The longwise measurement in Figure 10 shows as well hardly any changes in the surface. This confirms the previous experience that PU, when compared to PTFE filled with bronze, exhibits only minimal abrasiveness.

4.4 Friction force analysis

In the test, the friction of each chamber is recorded. The friction was analyzed with an average over 10 hours steps for each angular position. These 10-hour steps can be used to analyze the friction behavior over time. To ensure a good comparison between surface measurement and friction curve the last step was chosen and displayed in Figure 11.

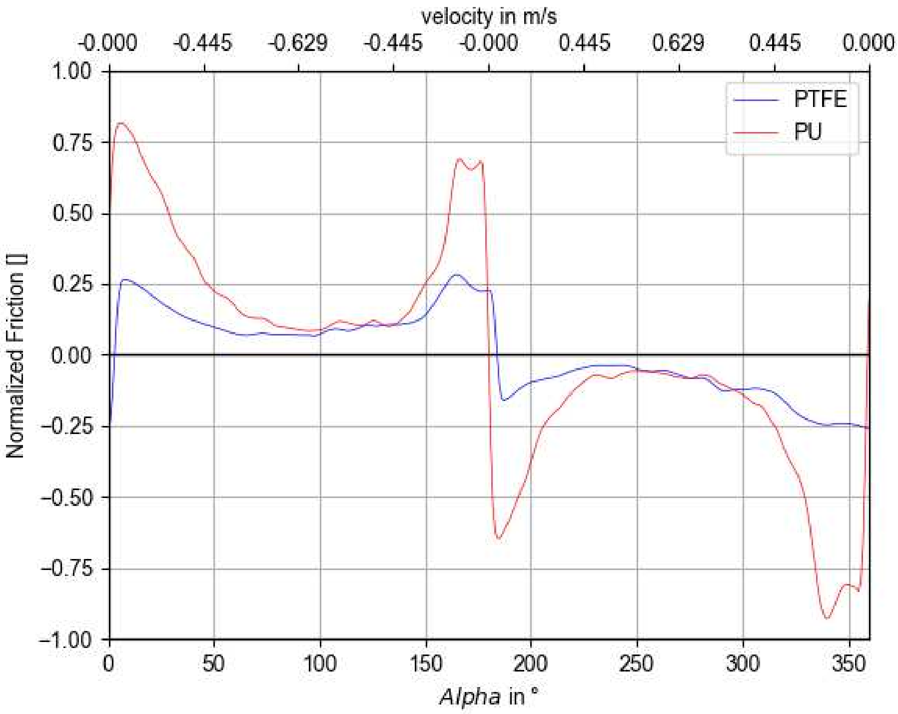


Figure 11: Friction force at end of test

The angular position is corresponding to a speed with a maximum speed at 90° and 270°. In this area, the friction of both materials is in a comparable range and indicating a lubricated contact area. This is corresponding to the scattered light measurements that shows less change in Aq compared to the region 3 at the stroke end. The turning points with less speed and change of direction are visible at 0° and 180° in the friction force plot. This corresponds to the areas with most change detected by the optical measurement. Based on friction and surface characterization the conclusion is a minimal fluid film close to dry running when the direction of movement is changing. In addition, the sliding properties of the general material classes are shown. The PU seal tends to have a higher friction in the areas of low/zero speed. This explains the stick-slip tendency of this material class compared to PTFE-based materials.

5 Summary and Conclusion

In summary, the use of a scattered light sensor ensures a more comprehensive image of a surface structure. Unlike conventional tactile measurements, which only provide information about the surface texture based on a very short measurement distance, this method presents a detailed picture of the distribution of roughness peak angles as well as the overall shape. When combined with traditional measurement techniques, it allows for a holistic view of the mating surface of a seal. The insights gained from these experiments are essential for making reliable statements about our requirements for a sealing mating surface.

In the future, the consideration of FFT (Fast Fourier Transformation) will be another area of focus, which is beyond the scope of this paper. Through Fourier transformation over the entire length of the rod, the shape and texture of the rod surface can be visualized. This will help exclude any unfavorable influences on the sealing function caused by surface waves, ensuring consistent and reliable quality control of the surface - a critical factor for effective sealing. Therefore, the goal is to incorporate both conventional and scatter light measurement values into surface finish specifications.

6 Nomenclature

Variable	***Description***	***Unit***
α	tilt angle of the light spot on the surface	[°]
φ	scattering angle	[°]
k	correction factor	[-]
$p(\varphi)$	normalized intensity distribution	[-]
Aq	variance of the scattered light distribution	[$°^2$]
n	total number of angle classes	[-]

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