Review

Description of the Pumping Rate of Shaft Counterfaces in the Sealing System Radial Lip Seal Using the 3D Parameters of ISO 25178

Cornelius Fehrenbacher*, Lothar Hoerl, Frank Bauer and Werner Haas

Institute of Machine Components (IMA), University of Stuttgart
Pfaffenwaldring 9, 70569 Stuttgart, Germany
*Corresponding author: cornelius.fehrenbacher@ima.uni-stuttgart.de

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The sealing system radial lip seal represents a complex tribological system with high requirements to be fulfilled over a long time. The surface texture of shaft counterface has a great influence on the performance of radial lip sealing system. A usability evaluation of shaft counterface with standardized 2D roughness parameters is not possible, because they represent only limited functional properties of the shaft counterface. With optical measurement instruments, shaft counterfaces can be measured in 3D. By using 3D metrology shaft counterface data the circumferential direction can also be evaluated. Together with the 3D surface parameters according to ISO 25178 this provides a fully new approach to evaluate shaft counterface. After the measurement, the data must be preprocessed to obtain meaningful parameters and to get a uniform database regardless of the manufacturing process. Measuring the pumping rate of shaft counterfaces is a common but time-consuming method to describe the quality of radial lip seals. For the evaluation of the 3D surface parameter according to ISO 25178 correlation analyses were performed by using a linear regression analysis. The correlation analyses have shown, that the 3D parameters have the potential to describe the quality of shaft counterfaces for sealing purpose.

Keywords: seals, ISO 25178, roughness, surface texture, surface analysis

1. Introduction

The sealing system radial lip seal consists of four components: the radial lip seal, the shaft counterface, the lubricant and the surrounding. This system represents a complex tribological system (Fig. 1).

The requirements, which have to be fulfilled, are high. Elastomeric radial lip seals are standardized in national [1,2] and international [3] standards. The membrane and the garter spring are widened during assembly the radial lip seal. Because of this, the sealing lip is pressed against the shaft counterface. During operation, a thin lubrication film is between the radial lip seal and the shaft counterface. Leakage is prevented by the dynamic sealing mechanism, based on a fluid flow from the air-side to the liquid-side of the radial lip seal. In addition, the seal must prevent dirt ingress into the machine [4,5].

The shaft counterface determines to a great extent the leak tightness of the sealing system, friction and wear and with that, the quality, working life and reliability of the sealing system. According to DIN 3760 [1] and ISO 6194 [3] the shaft counterface of a radial lip seal must be free of structures inclined versus the circumferential direction. Because these structures create also a pumping effect with superimposes to the pumping capability of the radial lip seal leading to a system failure by leakage or dry run.

Fig. 1 Sealing system radial lip seal

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Until today, shaft counterfaces for radial lip seals are evaluated by using 2D stylus metrology. Based on this 2D roughness traces 2D roughness parameters are determined. But the single determination of the surface roughness is not enough to determine whether a shaft counterface is suitable for the sealing system. Currently the measurement take place in 2D longitudinal direction. Important for the seal is however the circumferential direction. Additionally the 2D roughness parameters, e.g. $R_z$ or $R_a$, represent only limited orientated structures and functional properties of the shaft counterface.

Now the measurement includes the three-dimensional topography of a shaft counterfaces. The whole area which is in contact with the radial lip seal, can be evaluate. The tribological conditions of the sealing zone vary with the 3D roughness. The new standard for 3D surface parameters, the ISO 25178-2 [6] are based on optical surface metrology and evaluate the surface texture in three dimensions. This new standard shows high potential for the evaluation of shaft counterfaces. But until now there is only little knowledge available how and which of the parameters can be used to fulfill the needs of tribologists.

Therefore a research project has been started at the University of Stuttgart, which analyses the benefits of the new 3D surface parameters for the use in the field of sealing technology.

2. 3D parameter of ISO 25178

There is a constant development of optical measurement devices for the detection of surfaces topographies in three dimensions. As a result, the 3D parameters are becoming more and more significance. Since September 2012 the standard ISO 25178 [6] for extensive surface parameters is published. This standard defines five groups of parameters (Fig. 2). A full list of all 3D parameters described in ISO 25178 is found in the appendix.

2.1. Height parameter

The group of the height parameters is like the amplitude parameters of the two-dimensional surface parameters in ISO 4287 [7] and ASME B46.1 [8]. The roughness of all technical surfaces are determined based on these parameters, as well as the threshold values for roughness of the shaft counterfaces. Analogue to the amplitude parameters the three dimensional height parameters describe the roughness based on the height difference of the topography. The parameters are calculated either as a maximum value ($S_p$, $S_v$, $S_z$) or as an average value: The averaging can be place arithmetically ($S_a$) or quadratically ($S_q$). Take note the two dimensional parameter average roughness depth $R_z$ is not the equivalent to the maximum height $S_z$. $S_z$ is calculated from the sum of the peak height $S_p$ and the maximum pit height $S_v$. Therefore, $S_z$ is equivalent to the total height of the profile $R_t$.

2.2. Functions parameter

The function parameters are based primarly on the known two-dimensional parameters according to ISO 13565 [9] and were used directly to the three-dimensional description of a surface. These parameters are the based on the Abbott curve, which represent the material ratio of the surface area at each position of the height. New parameters are the Volume-Function parameters. Based on these parameters, the surface topography can be characterized based on the volume of material within defined limits ($S_{mr1}$ and $S_{mr2}$).

2.3. Feature parameter

The group of the feature parameters are new compared to the two-dimensional parameters. With this group the topography is described and evaluated by their area elements, hills and valleys. The definition of the elements comes from the geography and based on point, line and area elements (Fig. 3) [10,11].

Each hill has a highest point, the peak. Each valley has a deepest point, the sink. Peaks and sinks are point elements. If you connect a peak with the nearest peak of the neighboring hill on the shortest way, then a ridgeline forms. Analogue to this, you walk along a flow line if you connect two sinks. Based on these line elements, the area elements can be isolated. In the saddle point, the ridgeline and the flow line intersect. The height of a hill is defined as the height difference between the peak and the nearest saddle point. Similarly, the valley depth
between the sink and the nearest saddle point is determined. The surface is segmented into elements by using the watershed transformation. The surface is virtually flooded with water. In the deepest valley, the water level begins and increases. If the water level reaches further higher lying valleys, these are also flooded. Are two neighboring valleys fully flooded, they connect with each other in the saddle point. If you follow the further increase in the level of the border between the two lakes, one obtains a ridge line, the so-called watershed. The algorithm is performed until the water level has reached the highest peak and the topography is fully segmented. In the calculation, we obtain the sinks, the valleys, the saddle points and the ridgelines. To obtain the peaks, the hills and the flow lines, the topography is inverted and the segmentation is performed again. Each local maximum leads to a hill and each local minimum to a valley. These are interpreted as a surface element. To counteract this over-segmentation, small valleys and small hills must be grouped together. About decision trees, the relationship between peaks and sinks can be traced. The ISO 25178-2 describes for this the Wolf pruning [12]. According to ISO 25178-3 [13] the limit for the pruning is specified from 5% of $S_z$. From the segmented topography, the parameters are determined. For this purpose the height, the area and the volume from each hill and valley are determined. The average height of the five highest hills is the five-point peak height $S_{5p}$. Analogue, the five-point valley height $S_{5v}$ of the valleys is defined. The parameter ten-point height $S_{10z}$ results from the sum of five-point peak height and five point valley height. The number and kind of the hills are described with the peak density $S_{pd}$ and the arithmetic mean of the peak curvature $S_{pc}$. The exact method of calculating the peak curvature is not described in ISO 25178-2.

2.4. Spatial parameter

Using the spatial parameters, structure orientation on the surface can be described. Basis of the spatial parameters is the autocorrelation function and thereof the autocorrelation area. The topography is shifted against itself in the $x$- and $y$-direction. For the calculation of the parameters the form of the maximum in the middle of the autocorrelation area ($X = Y = 0$) is analyzed. The texture aspect ratio $S_{tr}$ is used to identify a predominant orientation of the topography. With this parameter you can describe whether the surface is isotropic or anisotropic (Fig. 4). The autocorrelation length $S_{al}$ describes the wavelength of the topography.

2.5. Hybrid parameter

The hybrid parameters are formed by the vertical height information as well as the lateral information of the topography. The root mean square gradient $S_{dq}$ describes the average slope. Topographies with high sidewall slopes (e.g. surfaces with many outbreaks) leading to high gradients. The parameter $S_{dr}$ is the ratio of the increment of the interfacial area of a surface over the sampling area. The interfacial area is calculated by the addition of all slope areas. At topographies with large sidewall slopes the interfacial area is bigger.

3. Shaft counterfaces

In this project differently manufactured shaft counterfaces were used (Table 1). The manufacturing parameters varied within each manufacturing process. The roughness of the shafts were between $R_z = 0.7…7 \mu m$. The entire test scope included over 150 shaft counterfaces.

3.1. Measurement

The shaft counterfaces were measured with different measurement instruments with different measurement methods. The measurement device must be able to measure the roughness of the shaft counterface. This requires a sufficient resolution in $x$-, $y$- and $z$-direction. Additionally, the measurement area must be large enough to capture a sufficiently number of structures on
the surface. At the Institute of Machine Components, a standard measurement area of $1 \times 1$ mm has been found to be sufficient. Furthermore a translational or a rotational stage should be provided to measure larger measurement areas by stitching single measurements. Each measurement device has its own advantages and disadvantages [14].

3.2. Preprocessing of the data

For the determination of two-dimensional surface parameters according to ISO 4287 and ISO 13565, the measurement conditions and the filtering of the raw data are standardized. For the determination of the three-dimensional parameters, there is no standardized approach. There is simply a description of the fundamental approach for the preprocessing of the measurement data in ISO 25178-3 [13]. In order to compare the data and to obtain meaningful parameters, the measurement raw data are preprocessed, analyzed and visualized with the Software “Mountains Map” from Digital Surf, which is industry standard. The whole process is display in Fig. 5. For this purpose, the cylindrical curvature of the shaft counterface and a position deviation are removed. The most common method to remove the cylindrical curvature, is the method of least squares. Measurement errors, peaks or holes, are still in the topography. These errors must be removed from the surface, because they can severely affect the parameters. Especially the height parameters ($S_p$, $S_v$, $S_z$), which are not averaged are greatly influenced by the peaks and holes. Due to the fact that the maximum height $S_z$ serves as a reference for the Wolf pruning, all feature parameters would be calculated incorrectly. By the intersection method peaks can be compensated. Most of the peaks and the holes are only a few data points. They contribute very little in proportion to the material fraction. Based on the Abbott curve, the heights can be cut off, which are outside of the range between 0.5% and 99.5% of the material ratio. These prepared surfaces can be used to determine and compare the each other.

4. Pumping rate tests

A common method to describe the quality of radial lip seals is to measure the pumping rate of shaft counterfaces. For this purpose, the method of Raab is used [15]. Therefore the lip seal is inversely mounted to the test rig. With changing rotational directions of the shaft counterfaces the pumped fluid is measured. Out of the difference of the flow rates, the pumping rate of the shaft counterface can be calculated. The measurement of the pumping rate with this method is only valid as long as the pumping rate of the radial lip seal is greater than the pumping rate of the shaft counterface. If it is not the case, in one rotational direction of the shaft counterface, a high fluid amount and in the other rotational direction no fluid amount is measured.

### Table 1 Shafts counterfaces

<table>
<thead>
<tr>
<th>manufacturing process</th>
<th>number of shaft counterfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plunge grounded</td>
<td>75 (hard) / 42 (soft)</td>
</tr>
<tr>
<td>Feed grounded</td>
<td>6 (hard) / 4 (soft)</td>
</tr>
<tr>
<td>Roller-burnished</td>
<td>5 (hard) / 10 (soft)</td>
</tr>
<tr>
<td>Shot-blasted</td>
<td>2 (hard) / 4 (soft)</td>
</tr>
<tr>
<td>Turned</td>
<td>24 (hard)</td>
</tr>
</tbody>
</table>

Fig. 5 Preprocessing of the measurement data
Additionally, this type of determination the pumping rate of shaft counterfaces is valid only under the assumption, that the pumping rate of the radial lip seal is independent of the rotational direction of the shaft.

5. Correlation of the data

For the evaluation of the 3D surface parameter according to ISO 25178 correlation analyses were performed. The relation between the 3D parameter and the target value was examined. This is done by using a linear regression analysis. The linear correlation coefficient between the various 3D parameters and the pumping rate of the shaft counterface, which were determined in the tests, are formed. A correlation value of 1 indicates an ideal linear correlation over all values. The aim is to obtain the best possible correlation between a surface parameter and the pumping rate of the shaft counterface, without considering the manufactured process. For this purpose over 150 different manufactured shaft counterfaces (grounded, turned, roller-burnished and shot-blasted) were considered.

5.1. Overview

In Fig. 6, the average correlation coefficient of each group of parameter of ISO 25178 is shown. If all shaft counterfaces are included in the evaluation, the correlation coefficients are lower compared to the individual evaluation of each manufacturing process. The exclusive viewing of the hard turned shaft counterfaces provide a good correlation coefficient. The best correlation coefficient with 0.7 provides the group of function parameters with the pumping rate of the shaft counterfaces. The more shaft counterfaces, manufactured with different manufactured parameters, the lower the correlation coefficient. The correlation between the surface parameters and the pumping rate of the shaft counterfaces decrease. A good correlation with the pumping rate of the shaft counterfaces provide especially those 3D parameters that describe the depth of structures or their volumes.

5.2. Plunge grounded shaft counterfaces

In Fig. 7, only the plunge grounded surfaces are regarded. It is obvious, that the correlation coefficient increases with a limitation of the selection of shaft counterfaces. In the group of the feature parameter (Fig. 8), the five-point dale height \( S_{5v} \) and the ten-point height \( S_{10z} \) correlates good with the pumping rate of the shaft counterfaces. Other parameters, like \( S_{ha} \) and \( S_{da} \), which describe the area of the hills and dales, correlate very poor. This dichotomy of “good” and “bad” parameters can be found in each group of parameters.
5.3. Result
To make a prediction about the pumping rate of shaft counterfaces, several parameters must be considered. It is not possible to predict the fluid transport of shaft counterfaces by using one 3D parameter. The surface texture is very different of each other depending on the manufactured process and manufacturing parameter. Depending on the manufacturing process the one or the other parameter correlate better with the pumping rate of the shaft counterfaces. The parameter $S_{td}$ (texture direction), which describes the direction of the structures on shaft counterfaces, correlated poorly with the pumping rate of shaft counterface. This is due to the calculation of this parameter. The calculation of this parameter based on the auto correlation function. The algorithm is not able to resolve the smallest and finest structures, which exists on the surface. Solely with the hard-turned shaft counterfaces the correlation with the $S_{td}$ parameter provides a high correlation coefficient.

6. Conclusion
The surface texture of shaft counterfaces has a significant influence on the pumping rate of shaft counterface in the sealing system and with that on the quality, working life and reliability of the sealing system. A usability evaluation of shaft counterfaces with standardized 2D roughness parameters is not possible, because they represent only limited orientated structures and functional properties of a shaft counterface. The limits, mentioned in different standards, within a good sealing performance can be achieved, are inadequate for shaft produced in different ways. With optical measurement instruments, shaft counterfaces can be measured in 3D. Together with the new surface parameters according to ISO 25178 this provides a fully new approach to evaluate shaft counterfaces. However, up to now there is only little knowledge available how and which of the parameters can be used to fulfill the needs of tribologists.

The described procedure for preprocessing the measurement data can be applied to every shaft counterface regardless of the manufacturing process and provides for the calculation of the 3D parameters a uniform database.

The correlation analyzes have shown, that parameters describing the height of dales and their volumes, provide good results. They have the potential to describe the quality of shaft counterfaces in radial lip sealing systems. For the holistic approach and functional characterization of shaft counterfaces several parameters must be considered simultaneously. The studies have shown that even with the best and most expensive measurement instruments, a sufficient description of shaft counterfaces with one of the 3D parameters in terms of leakage is still not fully achievable.

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