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Functional Behaviour of Different Back Structures for PTFE Shaft Seals



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1 Introduction

Many different types of seals are required in each engine and gear unit. One of these is the rotary shaft seal, which must seal the oil from the application against the environment under static and dynamic conditions. For an efficient and reliable application, no leakage and a long lifecycle have to be guaranteed. Therefore, a seal with a robust and reliable sealing effect is necessary.

Depending on the operating conditions, different shaft seals can be used, which differ mainly in design and material. Each of these shaft seals has its advantages and disadvantages in the area of static leak tightness, dynamic leak tightness as well as chemical and thermal resistance. A sealing ring that combines all the advantages does not yet exist. Consequently, the aim was to develop a seal which incorporates all the advantages of the existing seals without their disadvantages.

A detailed description of the new seal design has already been published by the authors at the 24th international Conference on Fluid Sealing 2018 /1/. Therefore, the description of the aim, the advantages and the functional basics (chapter 2 and 3) was taken from this publication.

2 Shaft Seals

Shaft seals need a back pumping effect for dynamic leak tightness. Thus, a radial shaft seal can be seen as a small pump when the shaft is rotating and fluid can be pumped back from the air side to the oil side. As a rule, rubber or polytetrafluoroethylene (PTFE) is used as the material for rotary shaft seals. The way the back pumping effect is generated varies depending on the material, which is why the design of the seals differs.

2.1 Elastomeric Lip Seal

State of the art for flooded, partially flooded or splashed shaft outlets from the machine housing are elastomeric lip seals according to DIN 3760 /2/ and DIN 3761 /3/. Important for the function of these seals is the rubber material and the two contact angles α and β shown in Figure 1. For a well working elastomeric lip seal the angle α on the oil side has to be larger than the angle β on the air side.



Figure 1: Elastomeric Lip Seal

Due to the two different angles the asymmetric seal lip creates an asymmetric pressure distribution in the contact area between seal and shaft. If the shaft rotates, the elastomer in the contact area is distorted in the direction of rotation (Figure 2). This distortion is asymmetric due to the asymmetric pressure distribution. In combination with the axial wear structures occurring with rubber materials, this results in threadlike directed roughness elevations. The oil will be deflected in axial direction at each individual directed roughness elevation. Because of the larger oil side angle and the resulting asymmetric pressure distribution more fluid is deflected towards the oil side then towards the air side. So the seal is able to pump back leakage /4/.



Figure 2: Back Pumping Effect – Elastomeric Lip Seals /4/

2.2 PTFE Lip Seal

Depending on the operating conditions, for example high sliding speed, high temperature or chemical attack, elastomeric lip seals reach their limit. In this case the material has to be switched to a higher grade material like PTFE. In order to reduce the creep tendency and improve the wear resistance fillers such as carbon or glass fibers are added to the PTFE material.

The PTFE lip seal is commonly manufactured as a flat disc. The inner diameter of the flat disc is smaller than the nominal dimension of the shaft. This causes elastic and plastic deformation of the PTFE lip when the seal is mounted on the shaft and gives the seal its final shape. The contact pressure of the seal is caused by the widening during the mounting process. Thus the static leak tightness is ensured. The disadvantage compared to elastomeric lip seals is the missing of any self-induced back pumping effect. For this reason, a PTFE lip seal without sealing aids can never be completely leak tight during shaft rotation. To solve this problem, a spiral groove is cut or embossed in the contact area of the lip (Figure 3).



Figure 3: PTFE Lip Seal – without Sealing Aids / with Spiral Groove

The PTFE lip seal with spiral groove acts like a screw seal and generates the desired back pumping effect for good dynamic leak tightness /5/. One disadvantage is the rotation direction dependence of the spiral groove. The main disadvantage is the lack of static leak tightness due to the groove being a potential leakage path /6/-/7/. For this reason, the PTFE lip seal with spiral groove cannot be used in flooded or partially flooded applications.

Improved static leak tightness can be achieved by adding an additional closed ring on the oil side in front of the spiral groove (5). Furthermore, lip seals have been developed and analysed which function bidirectionally /8/-/12/. For this purpose, sealing aids are stamped at the contact area of the PTFE lip seal (Figure 4).



Figure 4: PTFE Lip Seal with Bidirectional Sealing Aids /11/

The problem with the further development of PTFE lip seals with sealing aids is the robustness of these seals. Even small deviations due to production or mounting tolerances can lead to incorrect fitting of the sealing aids on the shaft. A reliable sealing effect is then no longer possible. The drawback in robustness compared to an elastomeric lip seals or a PTFE lip seals with spiral grooves is the reason, why these seals have only been used very rarely so far.

3 New design for shaft seals

Figure 5 sums up the advantages and disadvantages of the individual seals. The elastomeric lip seal is a good choice for a static and dynamic leak tight system because of its automatic back pumping effect. But the material sets the limits for the elastomeric lip seal. If a higher thermal or chemical resistance is required, the use of a PTFE sealing ring is recommended. A PTFE lip seal without sealing aids has a good thermal and chemical resistance and is leak tight statically. However, a PTFE lip seal without sealing aids will never be completely leak tight dynamically without additional aids. A spiral groove is recommended for good dynamic leak tightness. A static and dynamic leak tight PTFE lip seal can be achieved with sealing aids in the contact area. The drawback of these seals is their unrobust design. Even small deviations due to production or mounting tolerances lead to failure of the seal.

Sealing Ring Character-	Elastomeric Lip Seal	PTFE Lip Seal without Sealing Aids	PTFE Lip Seal with Spiral Groove	PTFE Lip Seal with Sealing Aids	Goal
Static				[]	
Tightness	+	+	0	+	+
Dynamic Tightness	+	_	+	+	+
Thermal and Chemical Resistance	_	+	+	+	+
Robust Design	+	+	+	_	+

Figure 5: Advantages and Disadvantages of Different Lip Seals

3.1 Goal

As a result, the aim of a new seal design is to combine the advantages of the existing seals. PTFE is to be used as a chemically and thermally resistant material. The static leak tightness of a PTFE lip seal without sealing aids is to be combined with the dynamic leak tightness of a seal with spiral groove in a robust and reliable design. To achieve this goal a new innovative approach is needed.

3.2 New Idea

The basis for the static leak tightness is to be provided by a smooth and shallow sealing gap in the contact area corresponding to a PTFE lip seal without sealing aids. A dynamic back pumping effect should therefore not be achieved by sealing aids in the contact area, as is the case with previous approaches. The new innovative idea is to create a self-induced back pumping effect by deliberately modifying the stiffness of the PTFE lip. To achieve these stiffness changes, the back of the seal will be structured (Figure 6).



Figure 6: PTFE Lip Seal – without Sealing Aids / Back Structured

3.3 Working Principle

The pressure in the contact area of the lip seal can be influenced by adding or removing material. The stiffness changing structures discussed in this paper have been realised exclusively by material removal. Are such structures applied to the back, they create self-induced the desired back pumping effect in the smooth contact area of a PTFE lip. Basis for contact pressure of the lip seal on the shaft is the elasticplastic deformation during the mounting process. Through specific implemented structures on the back of the lip the distribution of the contact pressure can be influenced in the desired way.

Figure 7 shows simplified the functional principle using the example of a rectangular specimen. The expansion results in a uniform constriction of the unstructured specimen. If the sample is structured, this influences the constriction behaviour. Depending on the alignment of the structures, constriction can also be achieved tilted to the direction of expansion. Such a tilted constriction leads to a tilted pressure distribution in the contact area of the PTFE lip seal.

Fluid always flows towards lower pressure. Therefore, a pressure peak deflects the fluid sideways in the direction of the lower pressure. Depending on the pressure distribution of the seal in the contact area, fluid dragged by the rotating shaft is deflected. Thus, on rotation fluid can be continuously deflected in axial direction by a pressure distribution tilted to the circumferential direction.

As a result, a PTFE lip seal with tilted structures on the backside is expected to selfinduce a back pumping effect and be dynamically leak tight, while simultaneously maintaining the static sealing performance.



Figure 7: Strain Behaviour of Rectangular Specimens

In order to convert the working principle into a functioning seal, 3D simulations were carried out prior to prototype production and test rig runs. The seals were designed for a shaft diameter of 80 mm.

3.4 First Prototype

As already shown in Figure 6, the first tested back structure was designed in the shape of a sickle.

Figure 8 shows the comparison between a PTFE lip seal without sealing aids and the new seal with recessed sickle shaped structures at the back. Compared to Figure 6, the view is directed from the shaft onto the seal. As expected, the contact pressure of the PTFE lip without sealing aids is a narrow line in circumferential direction of the shaft. Once fluid passes this line, the fluid can never be pumped back and leakage occurs.

Now let's have a look at the simulation of the new seal. The model is presented in a semi-transparent way to illustrate the position of the sickle shaped structures on the back.

In contrast to the lip seal without sealing aids, the contact pressure is at least partly tilted and no longer corresponds to a circumferential line. In areas, where the seal is structured at the back, the contact pressure on the shaft is interrupted. In addition,

the contact area is tilted according to the shape of the recessed structures on the back. As a result, deflection of the fluid flow back to the oil side is expected and the new seal should be leak tight dynamically.



Figure 8: Fluid Flow – without Sealing Aids / Back Structured

On the test rig the sickle shaped shaft seal showed a very high pumping rate and no leakage up to 12.000 rpm, whereas the lip seal without sealing aids showed leakage rates up to 50 g/h. According to the simulations the new seal has no closed contact pressure line. Nevertheless, the seal was able to remain statically leak tight against the tested 0W-30 oil. So the new seal design reached the set goal.

A more detailed analysis of the function and robustness, the prototype production and the experimental verification of the new seal design with sickle shaped back structures has already been published by the authors /1/. Furthermore, an elastichydrodynamic lubrication analysis of the fluid flow in the contact area of the new seal is published by DAKOV ET. AL. /13/.

4 Different Back Structures

The test runs with the sickle shaped back structures showed on the one hand very high back pumping rates and on the other hand no closed contact pressure distribution. This suggests that the shape of the structures can be further optimized in the direction of static leak tightness, while at the same time maintaining the dynamic leak tightness. In addition, a short time reverse run of the shaft without leakage should be possible.

4.1 Bending Line

Before the new structures were defined, the bending lines of different PTFE Lip seals with circumferential grooves were examined in a rotationally symmetrical 2.5D simulation. The aim was a wider contact area between the lip and the shaft. This should create more space to influence the pressure distribution through back structures in the desired way. The intended result was achieved by inserting two circumferential grooves, which nearly doubles the contact width from around 2.5 mm to 4 mm, Figure 9. With only one groove, the result was a strong bending of the lip at one position. As a consequence, the lip loses its elasticity in the radial direction and is therefore less able to follow a shaft runout. Furthermore, the strong bending quickly leads to the sealing ring tearing.



Figure 9: Bending Line without / with Circumferential Groove

4.2 Structures and Gap Height

Different back structures with a laser engraved depth of 30 % of the lip thickness were generated to analyse the functional behaviour. Figure 10 shows the form and the sealing gap height of four different back structures. The gap height was simulated using a 3D FEA mounting simulation.

The first structure is the already shown sickle shaped back structure. The gap height distribution shows that the sickle shaped back structures not only influence the pressure distribution (Figure 8) but also generate tilted channels in the contact area.

The second generated structure has the same sickle shaped structure combined with circumferential grooves. This change results in an increased contact area width, which generates longer channels. The sickle shaped and wide sickle shaped structures are applied 60 times around the circumference of one seal.

The third structure is shaped as a saw tooth. The structure is wider in the middle and narrower towards the outside. This takes into account the decreasing amount of expansion from the inside to the outside due to widening in the mounting process. The smaller the removed area in circumferential direction the more focused is the constriction under a back structure and therefore the generated channel height increases. So a saw tooth structure generates a channel in the sealing gap which gets higher towards the air side. A third circumferential groove helps to close the channel on the oil side of the saw tooth. Compared to the sickle and wide sickle only 20 saw tooth structures are applied on the circumference of one seal.

The last analysed structure is the saw tooth with doubled amount of structures applied to one seal. The more structures on one seal, the less stiff is the lip. As a result, there is less constriction at each back structure. Therefore, the channel height is smaller compared to the normal saw tooth design.



Figure 10: Analysed Back Structures with Sealing Gap Height

5 **Test Rig Run**

To analyse the functional behaviour of the different structures test rig runs were performed. The fixed operation conditions for all test runs were:

- Diameter 80 mm
- Shaft 100Cr6
- Surface Plunge Ground, Lead Free
 - Oil Fuchs Titan Supersyn 0W-30
- Shaft Centre Oil Level 120 °C
- Oil Temperature

5.1 Pumping Rate

In the first test run the pumping rate of the different back structured seals was measured. For this purpose, the lip seals were installed in reverse direction. Thus, there is now oil on the air side of the seal, which should be pumped to the other side by the seal. A high pumping rate is an indicator for a good dynamic leak tightness. Figure 11 shows the measured pumping rates. The sickle showed a very high pumping rate with up to 22.5 g/min at a speed of 4500 1/min. The wide sickle showed similar results with less pumping rate up to 3000 1/min and an increased rate at 4500 1/min. The high value at 4500 1/min may be due to the sealing ring floating up at higher speeds, which significantly increases the sealing gap and boosts the pumping rate of the wide sickle. For example, Gölz /12/, /14/ describes this shaft speed as critical speed.



Figure 11: Pumping Rate (inverse mounted seal)

Comparing the sickle with the saw tooth, the changed scaling must be considered. The saw tooth has a ten times lower pumping rate compared to the sickle. One reason for this is the significantly reduced number of structures on one seal. Furthermore, the closed ring on the oil side naturally leads to a throttling effect of the pumping rate.

5.2 Leakage

In a second test, the dynamic leak tightness was analysed. For this purpose, the seals from the pumping rate test were installed in the correct way and the leakage was measured stepwise at speeds of 1000 1/min, 3000 1/min, 6000 1/min and 9000 1/min. The duration per step was 2 h. None of the seals showed leakage.

Subsequently another leakage test was carried out with a longer duration of 72 h at a constant speed. The chosen speed was 6000 1/min, as PTFE lip seals without sealing aids show the most leakage at this shaft speed. The leakage was measured every 12 h. Figure 12 illustrates the measured leakage. Only the double saw tooth showed leakage. The amount of leakage decreased during the test run. After 48 h the double saw tooth showed no further leakage. As a result, the sealing effect seems to increase with the run in of the seal.



Figure 12: Measured Leakage

The sickle structure was further measured in an endurance test over 1000 h. As a result, no leakage could be detected. A pumping rate test after 1000 h operation showed that the pumping effect is maintained. This proves, the flat hydrodynamic channels remain active.

5.3 Reverse Run

The back structures discussed in this paper are designed for one-directional operation. However, a short time reverse run without sealing failure would be desirable. In order to determine the behaviour in the reverse direction, a short reverse run on the test rig over 10 min was performed at a shaft speed of 1000 1/min. Figure 13 shows the measured amount of leakage after 10 minutes. The sickle structure showed with more than 10 g/10min the highest leakage when the shaft is operating in the reverse direction. The reason for this can be seen in the gap height distribution in Figure 10. The sickle creates tilted channels on the oil side, which pump a particularly large amount of fluid towards the air side when running backwards. With the wide sickle these channels on the oil side are already significantly less distinctive. Therefore, the leakage is reduced by a factor of six. The saw tooth and double saw tooth have a nearly closed sealing gap on the oil side. As a result, both structures showed a small amount of leakage, which doesn't leave the sealing contact and could be pumped back when the shaft rotates forward.



Figure 13: Leakage in Reverse Run

6 Conclusion

Depending on the operating conditions, different shaft seals can be used, which differ mainly in design and material. Each of these seals has its advantages and disadvantages in the area of static leak tightness, dynamic leak tightness as well as chemical and thermal resistance. A lip seal that combines all the advantages in a robust and reliable way did not exist. Consequently, the aim was to develop a seal which incorporates all the advantages of the existing seals in a robust design.

For this purpose, the Institute for Machine Components (IMA) developed a new seal design. The new idea was to influence the lip stiffness through specifically adding or removing material on the back of the seal. These structures on the back influence the pressure distribution between the seal and the shaft in the preferred way. By creating a tilted pressure distribution, a back-pump effect is generated automatically.

Test runs with sickle shaped back structured shaft seals already showed very high back pumping rates and static leak tightness with a 0W-30 oil, although the generated channels in the sealing gap show no closed circumferential ring. This suggests that the shape of the structures can be further optimized.

New structures where generated and tested. Overall all the different back structures showed very good dynamic performances and no static leakage. This strengthens the idea of back structured shaft seals. The analysis further showed that the functional behaviour of the seal can be easily optimised for a specific operating condition. With the saw tooth, a new structure was generated which even remains dynamically leak tight during short time reverse runs.

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