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Development and long-term testing of pitch bearing seals for tidal energy turbines

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Generators producing electricity based on tidal energy have a considerable potential to support the transition to a fossil-fuel free economy. Seals in such applications face challenging operating conditions: Sea water as external media offers poor lubrication, where the operating pressure on these rotary seals can reach up to 5 bar. The main task for a reliable seal is therefore to safeguard water ingress into the bearing and prevent grease-leakage at the given pressure for the expected service period. A sealing material needs to deliver compatibility with the sea water, pressure and wear resistance.

Due to their excellent mechanical performance properties, Polyurethanes are a natural candidate for such an application, however challenged by the need of long-term media resistance in water and wear resistance under pressure in this starved lubrication condition.

As a first step, the effect of material ageing on wear resistance as consequence of hydrolysis induced degradation was studied in detail. For two candidate polyurethane grades, tribological samples were aged in hot water before testing their wear behaviour on a tribometer. It could be demonstrated how reduction of tensile strength as main result of a conventional immersion testing corresponds to wear resistance of the tribological test, with at least one of the two materials indicating superior chemical resistance to the water environment.

In a second step, prototype seals were designed and manufactured as basis of a comprehensive component test on an SKF in-house test rig. On this test rig, the long-term performance of the prototype sealing system was evaluated for an extended test time, with relevant properties like leakage, wear of the seals, running-in track of the countersurface being monitored at regular intervals. At the end of this test run, the seals were found to be in excellent condition, which corresponds to the interim findings of a pilot customer introducing the sealing concept to a field trial.

1 Introduction

Seals in tidal energy applications face challenging operating conditions: Sea water as media offers poor lubrication, where the operating pressure on these rotary seals can reach up to 5 bar. The main task for a reliable sealing system is therefore to prevent water ingress into the bearing and prevent grease leakage at the given pressure for the expected service period. Therefore, a sealing material needs to deliver compatibility with the sea water, pressure and wear resistance.

2 Theoretical background

2.1 Material ageing

In general, material ageing is characterized by physical and chemical ageing phenomena [1], [2].

Physical ageing affects the morphology of the polymeric material, such as crystalline structure, orientation, free volume and inner tension. Chemical and thermal ageing affects the backbone of the polymeric material and causes chain scission may lead to cross-linking. While chemical ageing is irreversible, effects of physical ageing can be partially reversible.

Depending on the polymeric backbone of a polyurethane, exposure to water may initiate hydrolysis. This is a chemical effect leading to chain scission, and gradually reduces the mechanical performance of Polyurethanes. Particularly Polyurethanes with ester-based soft segments are susceptible to this mechanism [3].

2.2 Wear resistance

Wear can be defined as continuous loss of material on a surface of a solid material as consequence of contact and relative movement to another material. The main wear mechanisms for sealing materials are adhesive wear and abrasive wear [4], [5].

Abrasive wear is material removal due to a grinding or cutting effect of a harder counter-surface on the softer sealing material. Adhesive wear is the formation of local bonding of two surfaces and consecutive separation within the material showing adhesive wear, leading to material transfer.

Multiple factors affect wear mechanisms, such as the material wear resistance as a material property, the lubrication situation, the roughness of the countersurface as well as operating speed and pressure influence. In many cases, it is not possible to distinguish a clear wear mechanism due to the superposed presence of various wear modes [5].

There are various approaches to quantify wear. DIN ISO 4649 creates mostly abrasive wear, however can be influenced by plasticizers of rubbers which lead to misguiding results [6], [7]

A test set-up using a tribometer as described in chapter 3 allows a specific selection of speed, contact pressure, and surface roughness.

Still, it remains a challenge to representatively replicate the real operating conditions, particularly in terms of setting up the lubrication situation, which is why validation testing, either on a component test rig or in the real application, is inevitable for final assessment of wear.

3 Experimental set-up

This study follows two main targets. In the first part, material samples of candidate polyurethanes were exposed to hot water to achieve a defined condition of degradation initiated by hydrolysis. These samples were then tested on a specially developed tribometer test set-up to characterize the wear behaviour as function of material degradation.

In the second part, the most suitable material identified in the first part was selected for manufacturing of prototype parts. These were then tested on a component test rig to evaluate the performance as close as possible to the real application.

3.1 Materials

3.1.1 Polyurethanes

Two thermoplastic polyurethanes (PU1, PU2) with known differences in resistance to hydrolysis were selected for the study of wear resistance depending on state of degradation, with properties shown in table 1. As the required large diameter seals could not be injection moulded with mentioned Pus, the component testing described in chapter 3.4 was carried out using a cast polyurethane (PU3), which is similar in composition to PU2 and is known to show comparable resistance to hydrolysis.

Table 1: Recommended service temperatures

Material designation	Shore A hardness, points	Maximally recommended service temperature in water, °C
PU1	95	40
PU2	95	90
PU3	95	90

3.1.2 Rubbers

As a rubber alternative, an NBR-rubber grade with a Shore A- hardness of 85 was selected and is referred to as NBR1. Given the NBR turned out not to be suitable for the boundary conditions set-up for the polyurethanes on the tribometer due to too low material stiffness, this material was only used as benchmark material on the component test rig.

3.2 Immersion test set-up

Standard immersion testing was carried out based on ASTM D471 [8] for both Polyurethane materials. Specimens needed for tribology testing were immersed in addition to the standardized specimens needed for testing of volume change, hardness change, and change of tensile properties.

Polyurethanes show limited physical ageing effects when immersed in water, and therefore volume change and hardness change was minor. Reduction of tensile strength was used as main indicator for the assessment of progressing degradation. Immersion times were selected in a way to reach a reduction of tensile strength of more than 50%.

To give respect to the different resistance to hydrolysis, samples of PU1 were immersed at 80°C for times up to 1000h, and samples of PU2 were immersed at 100°C at times up to 3168h. These conditions were selected in a way to achieve minor reduction of strength (condition A), moderate reduction of strength (condition B) and severe reduction of strength (condition C).

3.3 Tribological set-up

The tribological tests were performed on a precision rotary tribometer (TE-93, Phoenix Tribology Ltd., Kingsclere UK), using ring-on-disk type specimen geometry that was specifically adapted for testing Polyurethanes with high wear resistance, with details described in [9].

Table 2 gives an overview on the selected test parameters.

Table 2: Test parameters for Tribometer testing of Polyurethane Specimens

Load (N)	166 (equivalent to 1 MPa contact pressure)
Speed (m/s)	0.25 (100 rpm)
Testing Time (h)	4
Lubrication	Dry
Roughness counter-surface, Ra (µm)	0.03

The main results evaluated were (1) the wear rate, which is derived from the total mass loss of the specimen during testing and (2) the average coefficient of friction during the test.

3.4 Component test rig

For component testing, the test rig RP5 of the SKF test lab in Judenburg, Austria, was used. It was specifically developed to test slewing bearing sealing systems with a diameter of 1000mm. Figure 1 shows the test rig and the seal assembly that is used for testing.

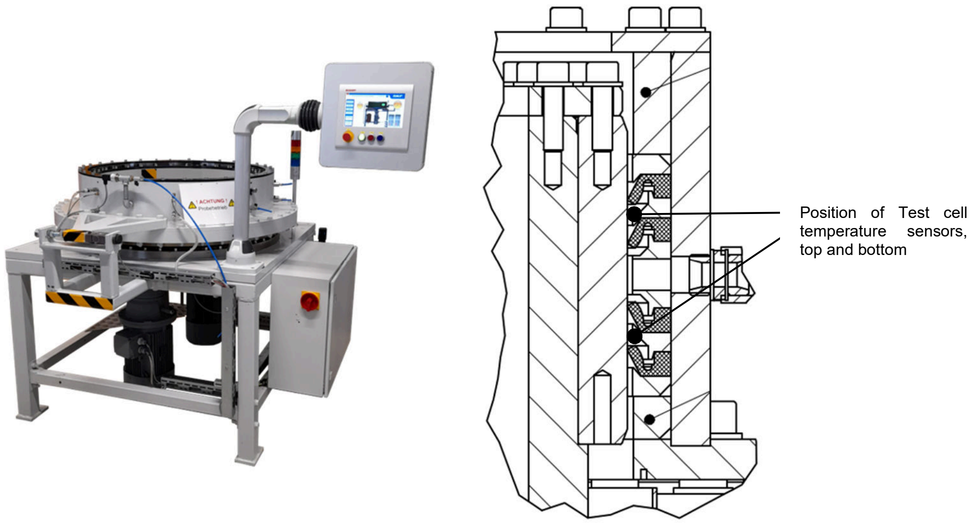

Figure 1: Test Rig RP5 with seal arrangement

Table 3 shows the test conditions used for the component testing.

Table 3: Test parameters used for component testing

Test media	Clear water, interim chambers with initial grease lubrication
Water temperature	10°C (permanently, actively cooled)
Test pressure (bar)	3
Test speed (rpm)	8
Shaft diameter (mm)	1000
Test duration (h)	1800
Displacement (mm)	0.1 dynamic run-out (DRO)
Shaft surface	Duplex steel, fine-turned and polished
Running direction	CW/CCW, weekly alternation

During the measurements, friction torque M and test cell temperatures (top and bottom) were permanently recorded. After the test, a visual inspection of both the seal (wear, signs of ageing) and the shaft surface (run-in marks) was carried out. Final inspection results for the NBR grade will be shown at the conference.

4 Results

4.1 Immersion testing

Table 4 and 5 show the change in properties for PU1, immersed at 80°C in distilled water, and the change in properties for PU2, which was immersed at 100°C.

Table 4: Change of properties for PU1 over time, immersed in distilled water at 80°C

Property	A: 168h	B: 336h	C: 1000h
Change of Hardness, Shore A pts	-1	-1	-1
Change of Volume, %	+1.74	+1.39	+1.45
Change of Tensile strength, %	-16	-36	-83
Change of Elongation at break, %	-2	-6	-76

Table 5: Change of properties for PU2 over time, immersed in distilled water at 100°C

Property	A: 168h	B: 1512h	C: 3168h
Change of Hardness, Shore A pts	-1	-2	-2
Change of Volume, %	+1.34	+1.37	+1.05
Change of Tensile strength, %	-18	-34	-57
Change of Elongation at break, %	+3	+22	+36

Despite the 20°C higher immersion temperature, the hydrolysis resistant PU2 took a much longer time to reach the severe reduction of tensile strength (a typical failure criterion would be a reduction of > 50%).

4.2 Tribological testing

Table 6 shows the tribological results obtained with unaged material specimens and aged specimens with different states of degradation. The ageing condition is thereby referred to as A, B, and C, corresponding to properties given in tables 4 and 5.

*Table 6: average coefficient of friction (CoF) and wear rate of PU1 and PU2, tested in Ring-on-Disk set-up under dry conditions, *specimen broken*

Material	CoF, PU1, /	CoF, PU2, /	Wear rate, PU1, $10^{-8} cm^3/Nm$	Wear rate, PU2, $10^{-8} cm^3/Nm$
New	0.88	1.25	0.25	3.58
Condition A	0.93	1.10	0.62	10.18
Condition B	0.88	0.81	0.36	572.77
Condition C	0.89	1.05	144.7*	695.06

It can be seen that as a general trend, the wear rate increases with progressing material ageing. Both materials showed strongly increased wear rates in condition C, however both the absolute level of the observed wear rate as well as its increase with progressing degradation was material specific and non-linear.

Figure 2 shows the specimen surface after the tribology test for PU1.

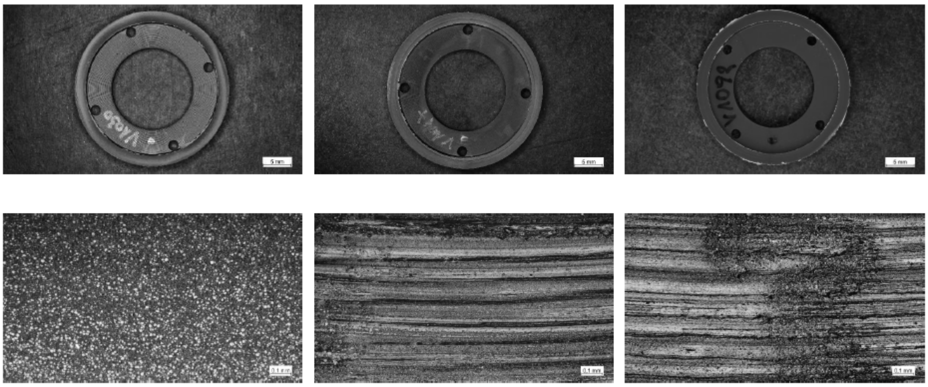

Figure 2: Wear pattern of PU1 in states new, A and B

Figure 3 shows the specimen surface of PU2 after tribological testing.

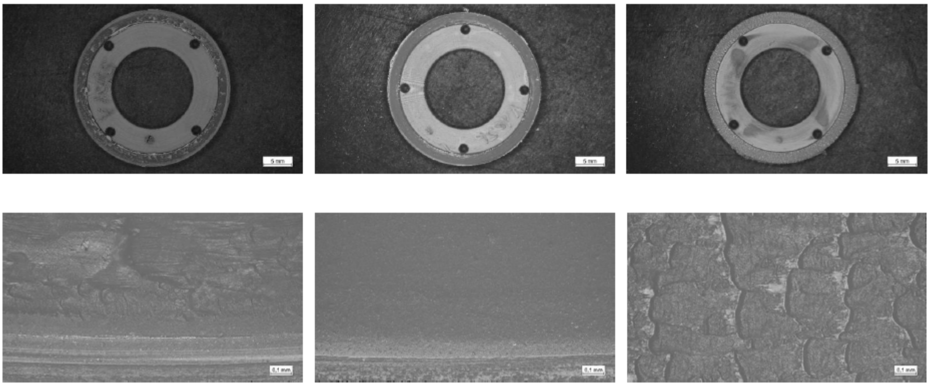

Figure 3: Wear pattern of PU2 in states new, A and B

It can be seen that PU1 shows wear tracks, indicating mostly abrasive wear. PU2, particularly in state B, shows indications of adhesive wear in addition to the abrasion. Although a definite statement is tricky with tribological experiments, this difference in the wear surface corresponds to trend of higher coefficients of friction found for PU2.

Although the overall tribological performance of PU2 was slightly worse in these tested dry conditions compared to PU1, the importance of hydrolysis resistance was ranked more important for the application as slewing bearing seal running in sea water. Therefore, a cast-counterpart version of PU2 was selected for the component tests.

4.3 Component test rig

Figure 4 shows the measured signals with 4 installed seals of PU3, where two seals were pressurized and 2 seals acted as back-up seals.

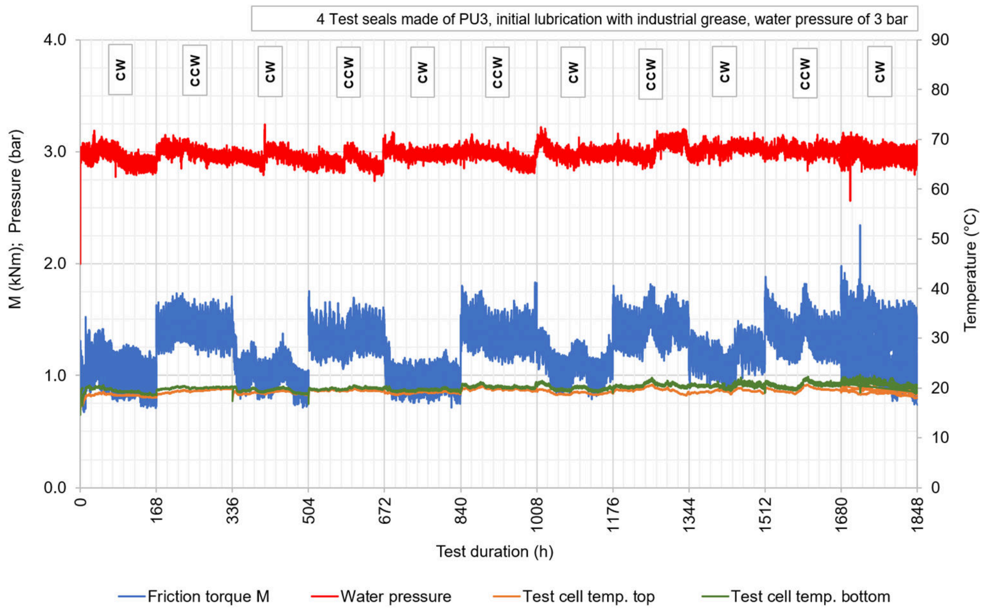

Figure 4: Signals for friction torque, speed, water pressure and test cell temperature for component test assembly with 4 seals of made of PU3, thereof 2 pressurized by water pressure

Figure 5 shows the measured signals with 4 installed seals of NBR1. Again, 2 seals were pressurized and 2 seals acted as back-up seals.

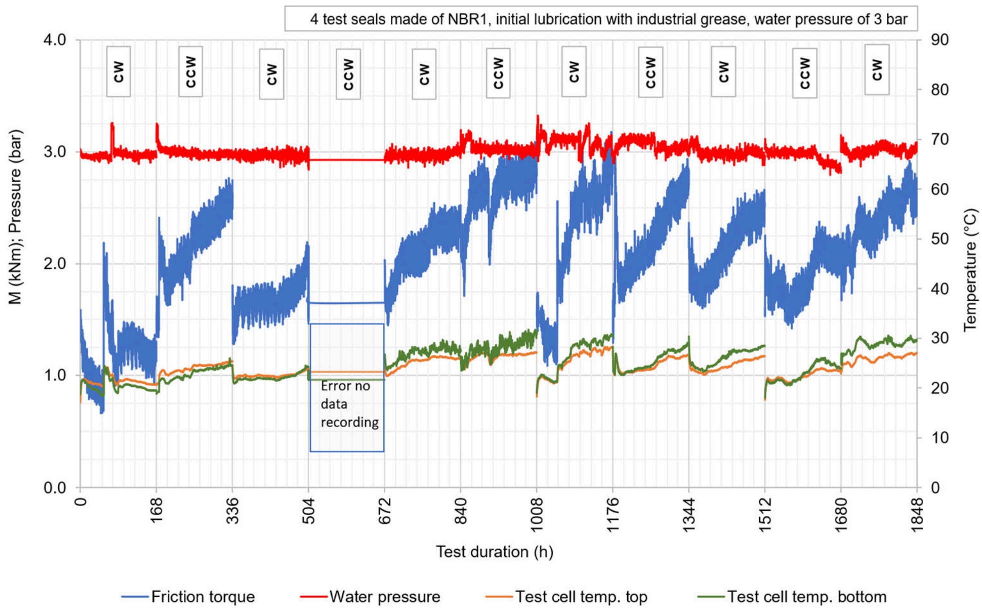

Figure 5: Signals for friction torque, speed, water pressure and test cell temperature for component test assembly with 4 seals of made of NBR1, thereof 2 pressurized by water pressure

The rotational direction was changed between clockwise (CW) and counter-clockwise (CCW) on a weekly basis for both materials. As this was a manual process, a standstill-time with a slight variation was inevitable. This can be seen by decreasing temperature signals, particularly with NBR1, where the friction level of the seals led to gradual temperature increase. In case of PU3, the temperature conditions were mostly stationary.

The main difference of the two materials was observed in a significantly varying friction torque, with the level of NBR1 being considerably higher. While PU3 was mostly operating between 1 and 1.5 kNm, NBR1 regularly exceeded 2 kNm and reached peak levels of up to 3 kNm.

Figure 6 shows the analysis of PU3 sealing lips after the long-term testing, compared to the original seal.

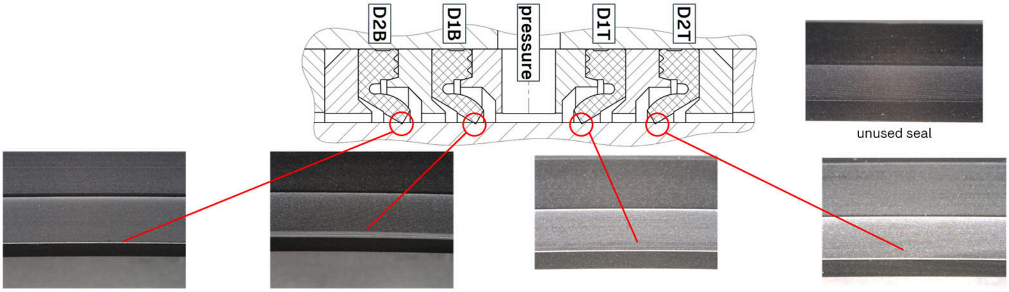

Figure 6: Visual inspection of sealing lips of PU 3 after long-term testing, seals at position D1T and D1B were pressurized with 3 bar water pressure, seals D2T and D2B were acting as back-up seals

The observed wear was marginal. For the seals running without pressure, hardly any signs of operation could be found, and the centre seals pressurized with 3 bar water pressure showed minor signs of wear at the sealing lip. The initial grease lubrication was still fully present, and no traces of water were found in the grease which indicates that the center seals D1T and D1B were sealing without leakage for the whole testing time.

Comparably low wear was observed with the NBR seals, and final examination results will be presented at the conference.

5 Summary and Conclusion

Wear behaviour is a crucial property of sealing systems, where the wear resistance of a sealing material in the application operating conditions gives a relevant contribution to the performance of the sealing system. It could be shown that the ageing condition of polyurethane significantly affects their wear resistance, with progressing degradation over-proportionally increasing observed wear rates.

Consequently, the hydrolysis resistance of a polyurethane needs to be considered in the material selection for an application permanently operating in water such as slewing bearing seals in ocean turbines.

Due to the selection of a hydrolysis resistant PU grade for component testing and a comparably moderate water temperature (even in the hottest areas of the world, the sea water temperature at a typical depth of 10-20m is expected to be below 30°C), no hydrolysis is expected to occur during the service time.

Unlike the tribological tests that were done in dry state for PU1 and PU2, the component tests were done with an initial grease lubrication, as is typically used in the real application. The overall situation of grease lubrication and pressure condition led to an operating condition where neither of the materials, PU3 or NBR1, showed relevant wear.

The main distinction between both materials was the measured friction torque, where NBR1 showed significantly higher torque values. Although wear does not seem to be a limiting factor for either material, a machine designed to harvest tidal energy aims for friction torque loss to be as low as possible. Therefore, the PU3 material was found to be better suited compared to NBR1, and was consequently selected as material choice for installation at a pilot customer site.

6 Nomenclature

Variable	***Description***	***Unit***
Ra	Surface Roughness	[µm]
CoF	Coefficient of Friction	[-]
M	Friction Torque	[kNm]

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