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Predicting seal lifetime: Effect of material loss during application on product performance

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Predicting the lifetime of polymer seals is critical for ensuring reliability and minimizing unplanned maintenance. In many applications, material loss during operation – caused by mechanical wear or exposure to aggressive environments – leads to gradual degradation of seal geometry and performance. This work presents a simulation-based approach to predict seal lifetime by modelling material loss and its impact on sealing performance. Finite element analysis (FEA) is combined with physically motivated models to capture two key degradation mechanisms: sliding-induced wear in rotary seals and material removal in erosive environments such as plasma etching. The resulting geometry evolution links directly to performance metrics, including sealing force. The methodology is calibrated using laboratory experiments, enabling the extrapolation of short-term test results to long-term behavior. The approach shows good agreement with experimental observations and allows reliable prediction of seal performance over time. Overall, this framework supports predictive maintenance and design optimization by providing a unified method to assess seal degradation under different operating conditions.

1 Introduction

Polymer seals play a pivotal role across many industrial applications, especially in maintaining vacuum integrity through both static and rotary seals. Predicting seal performance provides a valuable opportunity to design components that achieve an extended lifetime.

Predictive maintenance, which anticipates wear and cracks or potential failures before they occur, is rapidly gaining interest across many industries. Any seal failure or degradation that compromises application integrity can lead to significant production losses, yield reduction and costly repairs. By implementing predictive maintenance (PM) through advanced simulation methods, manufacturers can proactively identify when seals or other critical components are likely to degrade, allowing them to intervene before performance declines or failures occur.

Simulation-driven predictive maintenance insights are also instrumental in design and development cycles, enabling original equipment manufacturers (OEMs) to quickly optimize maintenance intervals with less reliance on costly and time-consuming physical testing. PM therefore enhances equipment uptime, productivity and profitability, making it a cornerstone of operational efficiency in advanced industrial equipment.

In this work, we introduce an advanced simulation method aimed at enhancing the predictability and resilience of polymer seals. The method predicts seal lifetime by simulating material loss as encountered in rotary shaft seals or in static seals exposed to erosive processes. The wear simulation is performed first to model the rotational wear that occurs in gearbox or pump applications.

The erosive media mimic the external conditions that cause wear. This wear model is then applied to the case of plasma media in etching processes. In this context, our approach leverages simulation methods that compress weeks of testing data to forecast years of seal function. These simulations not only help improve maintenance cycle optimization but also support the long-term cost-efficiency of operations.

2 State of the art

2.1 Modelling wear over time using finite element analysis

Archard's law [1] is a simple wear model in which the volume of wear debris Q is proportional to the normal force W, the slide distance L and Archard's wear coefficient K, which describes the debris-producing properties of the contacting surfaces. K encompasses variables such as temperature, roughness and sliding speed. Q is also inversely proportional to the hardness of the softer of the contacting materials, H.

$$Q = \frac{KWL}{H} \tag{1}$$

Schmidt [2] applies Archard's law to simulate the wear of O-Rings in dynamic applications. A UMESH user subroutine was developed in Abaqus, which changes the mesh during an iterative, time-dependent implicit FEA simulation [3]. In each iteration, the mesh is updated according to the wear that has occurred. A global parameter controls how much wear depth is allowed in each iteration. Dassault Systems has also developed its own proprietary algorithm based on Archard's law and included it in their FEA solver. We apply this second method for better integration into future Abaqus releases.

Considering the output of these simulations, not only can the change in shape be predicted, but also the change in the performance of the seals via the sealing force.

2.2 Simulating Erosive Effects on Elastomeric Seals

Plasma is a highly erosive media used in semiconductor manufacturing. However, plasma exposure also affects elastomeric seals (Figure 1), leading to plasma etching that often limits seal lifespan. Plasma produces two distinct types of etching. The first is chemical etching, which is driven mainly by radicals in the plasma. These radicals chemically alter the surface of polymer materials, which may change their physical properties and can lead to the detachment of small molecules. The second type is physical etching, which involves the bombardment of the surface by high-energy ions. These ions are effective at removing material from the surface, usually leading to etch rates much faster than those from chemical etching alone.

Figure 1: View of an O-Ring section sealing a plasma chamber, removed after 26% weight loss

Each plasma environment exhibits different rates of material loss from chemical and physical etching on a given polymeric seal, depending on the chemical plasma used (e.g. O_2, Ar, NF_3), the type of plasma source (e.g. remote plasma source, capacitively coupled plasma source), the input power, the chamber pressure, the gas flow rate, the plasma flow rate and the seal geometry. Weikart and Yasuda [4] observed a constant etch rate for various polymers in an O_2 plasma process. This means that the material removal rate for elastomers can be reliably predicted over an extended lifespan for different geometries. In our simulation method, instead of separately addressing the contributions from each type of medium, we focus on the overall effect of erosive media through material testing. The Archard wear model applied to radial shaft seals can be transferred to particle erosion by external media. The degree of etching can then be used to accurately forecast the lifetime of seals in plasma etch environments.

3 Wear bandwidth of rotary sealing systems

This work introduces a finite element method specifically designed to predict the lifespan of rotary sealing systems used in vacuum pumps, where the primary failure mode is surface wear of the seal. The geometry of the simulated elastomeric rotary seal is shown in Figure 2, where the shaft diameter d is 38 mm. A Nitrile Butadiene Rubber (NBR) material was used for the wear simulation, which was evaluated over 83 days. The average rotational speed during this period was 2,000 rpm.

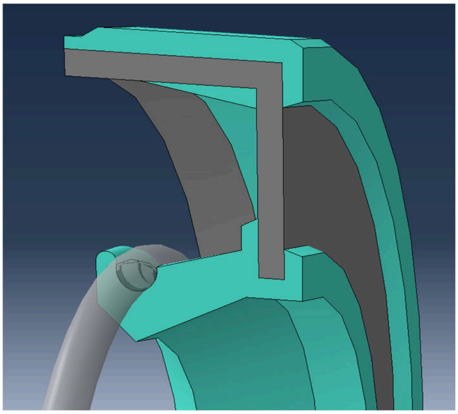


Figure 2: Rotary elastomer seal, d = 38 mm

Results from the simulation were first compared with physical measurements of a real seal. In application, the rotary seal is assembled with a spring to increase the radial sealing force, which the FEA simulation can account for. The radial force value was compared with a physical measurement of a real seal, as shown in Figure 3. The simulation and the measurement show minimal differences, including in the case where the spring is removed.

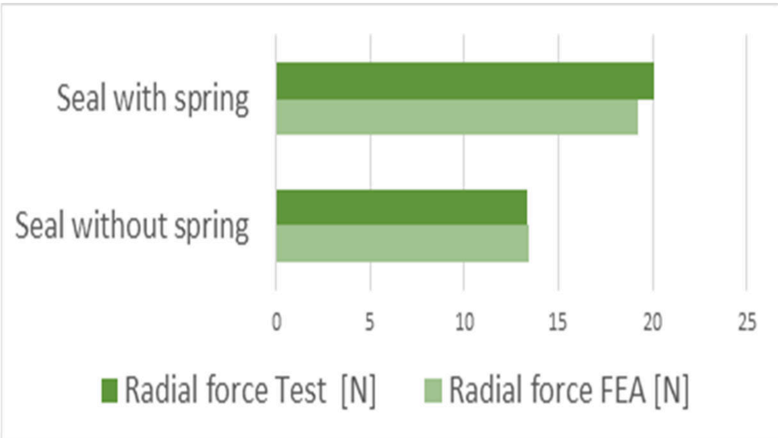


Figure 3: Radial force comparison, rotary elastomer seal, d = 38 mm

Figure 4 shows the calculated inner diameter when the spring is assembled. The close agreement between the simulation results and the measurements confirms that both the spring and the material have been modelled with high accuracy.

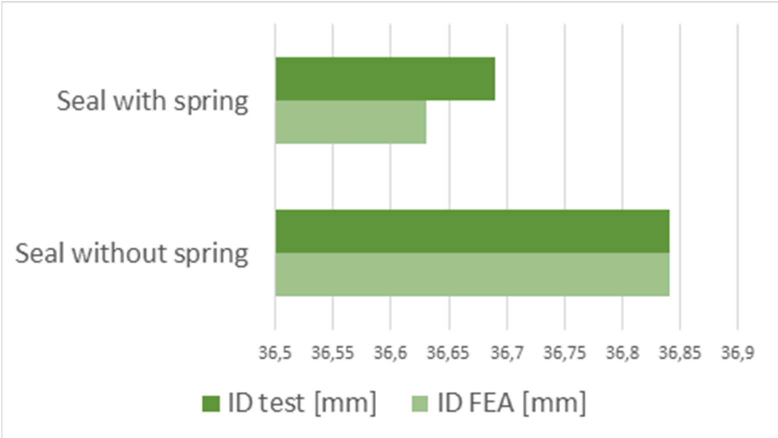


Figure 4: Measured and simulated inner diameter before test (unworn)

The following section presents the simulation results for the wear bandwidth. For this simulation, we calibrated an Archard wear coefficient of $K = 0.43 \cdot 10^{-11}$ mm^2/N on diameter measurements. The wear layout is displayed in Figure 5, showing significant wear on the sealing edge after 80 days.

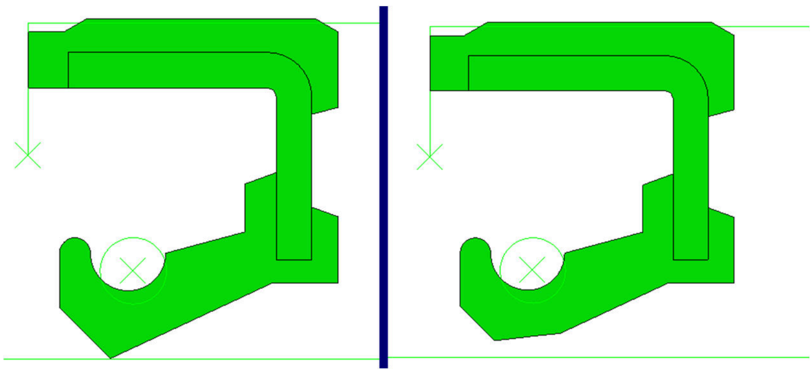


Figure 5: First method results of wear simulation, unworn RSS (left) and worn RSS (right)

We ran additional validation tests with a seal dimension scanner, see Figure 6 below.

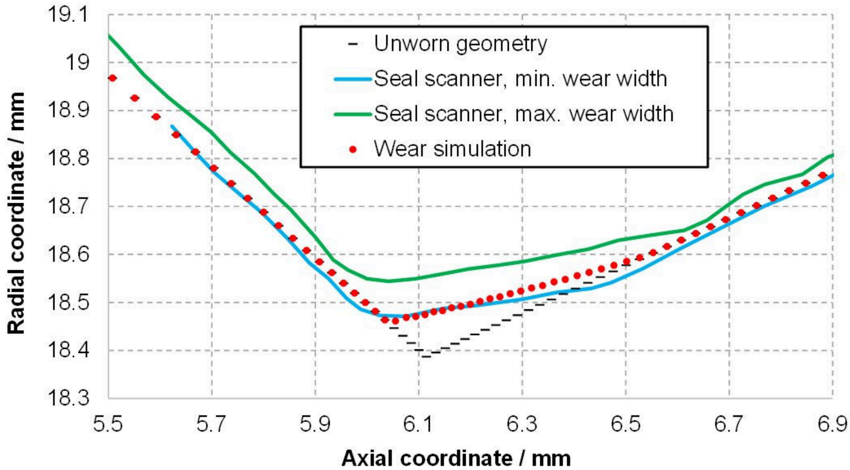


Figure 6: Comparison of the predicted seal profile after the duty cycle with the measured seal profile

Both the diameter and the layout match the measurements, so we decided to use this method to calibrate wear coefficient.

The worn layout and diameter give a radial load and contact pressure to predict performance after the run-in period.

4 Modelling plasma etching of static seals

Elastomeric O-Rings typically etch into a concave shape, as shown in Figure 1. Based on this, we assume a parabolic distribution of the reactive species that cause the etching, see Figure 7. This is achieved by varying the applied pressure along the seal profile in the wear simulation.

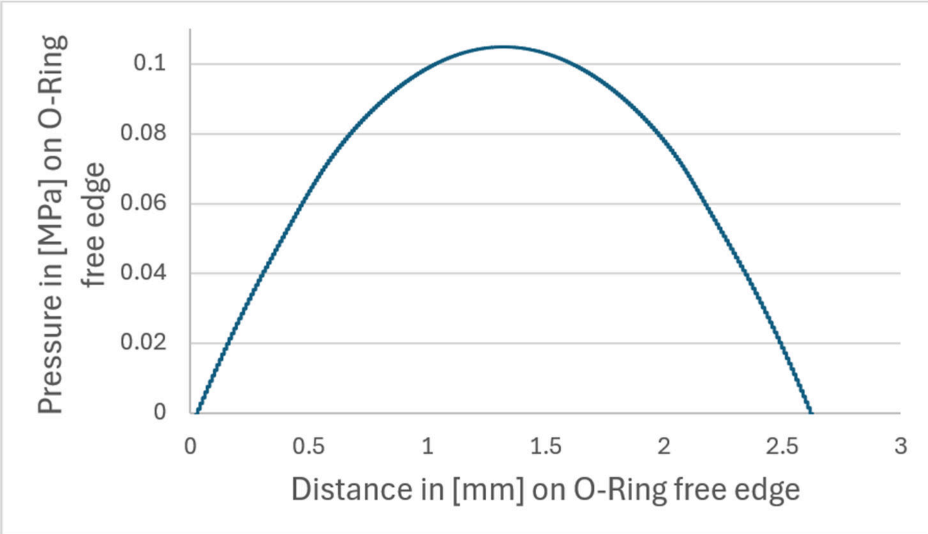


Figure 7: Hypothesis of pressure applied by radicals over the free edge

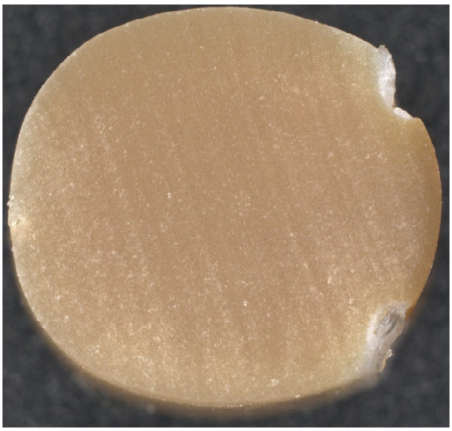
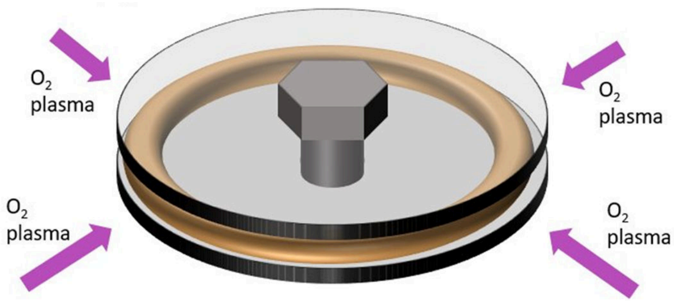


Figure 8: View of an O-Ring cross-section sealing a plasma fitting

To obtain an etch coefficient K_{etch}, we initially studied a section of an FFKM O-Ring that had been used in a real O_2/NF_3 plasma etch process (Figure 8). The FFKM seal was installed for two months, which approximates 560 hours on the assumption that the tool was run for ten hours a day. The volume of material etched in this scenario corresponds to around 2% of the total seal volume. Based on the geometry of the seal in application, we fitted the etch coefficient K_{etch} to 2,000 mm² N^{-1}. We project this coefficient to reach 10,000 mm² N^{-1} for 2,800 hours. This projection will be validated through an ongoing test campaign, in which we are conducting plasma etch tests on the same FFKM material to obtain a physical etch rate to compare with our simulation results.

Operating the plasma chamber with a seal for 2,800 hours was not feasible within the scope of this study. We had to accelerate the volume loss by increasing the exposed area. We used a compression set fixture to apply 10% compression and then installed inside the chamber. We can use this to characterize the etching parameter, see Figure 9.



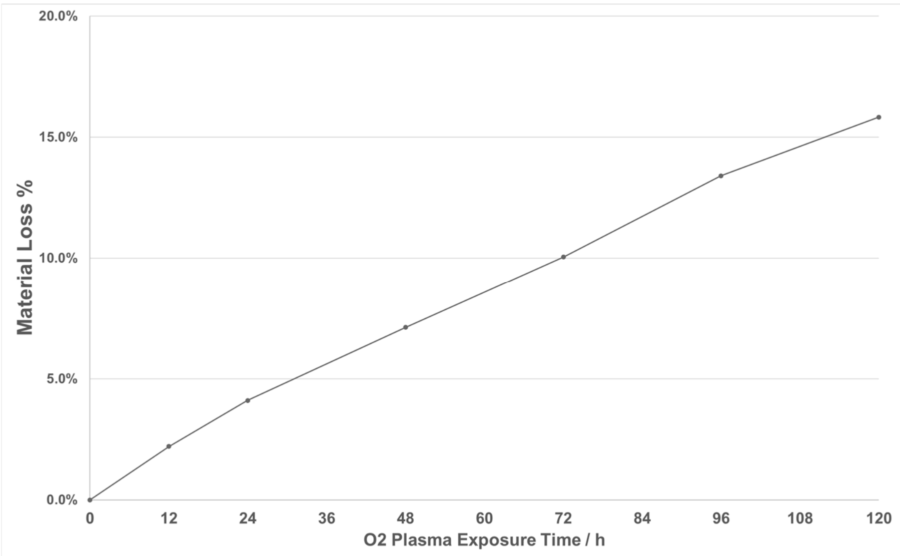


Figure 9: Seal accelerated etching setup and test results of material loss as a percentage of and FFKM O-Ring at 10% compression

We fitted the etch coefficient to reach simulation convergence, using a flat etching front, to a 13% material loss, which corresponds to 96 hours etching under the same conditions as our test equipment, see Figure 10.

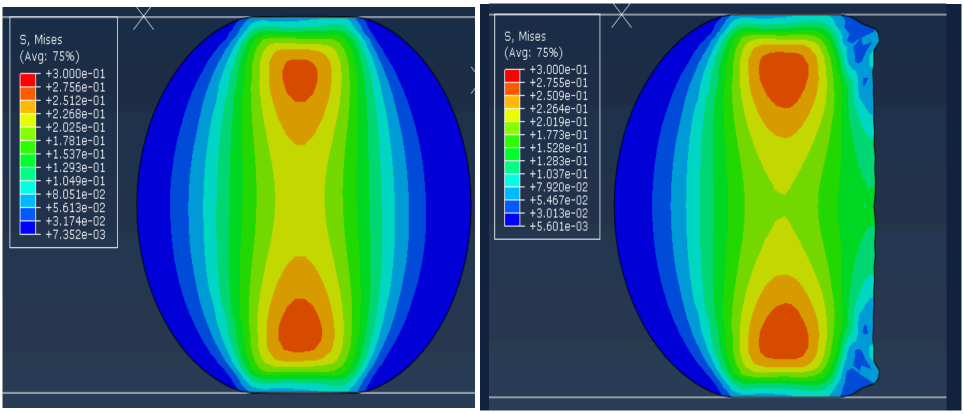


Figure 10: 13% material loss in percentage tested for a Isolast® PureFab™ JPF10 O-Ring at 10% compression

We now need to gather in-situ test data from partners' industrial etching equipment to check how accurate the method is for a seal in a real groove, where plasma will arrive from one of the corners.

5 Summary and conclusion

This work focuses on the effects of material loss, namely wear and plasma etching, on elastomeric seals. The study describes the mechanisms of wear in elastomers and the impact of plasma flow on etching. It also provides an overview of existing research on wear modeling.

- The Archard model is used to develop a numerical method that captures wear behavior within a FEA framework. This method is applied to a rotary elastomer seal used in vacuum chambers. The Archard model successfully predicts the wear behavior of a NBR material. The FEA-based approach provides accurate wear analysis after prolonged use and predicts the reduction in sealing force. Integrating thermal aging is a natural next step to check it impact on sealing force.
- The same wear model is then adapted to predict the material loss due to plasma etching, where plasma acts as the external factor contributing to wear. This newly developed method for etching prediction, based on the wear model, shows promising results.
- Both methods can help to optimize maintenance periods and thereby achieve higher efficiency.

Future studies should focus on extending this method to other wear calibration tests or checking coefficients for other plasma types. The approach could also be enhanced by incorporating additional physical and chemical effects. For example, the material model could be updated to include the Mullins effect, enabling the inclusion of damage from cyclic loading and compression set in the FEA analysis.

6 Acknowledgment

The authors would like to sincerely thank Dr. Christoph Wehmann for developing the wear method that was initially used at Trelleborg Sealing Solutions.

7 Nomenclature

Variable	*Description*	*Unit*
Q	Wear debris volume	[mm^3]
L	Sliding distance	[mm]
W	Normal force	[N]
H	Hardness of soft material	[-]
K	Archard's wear coefficient	[mm^2/N]
K_{etch}	Etching wear coefficient	[mm^2/N]

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