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VISUAL FAILURE ANALYSIS METHODS OF DYNAMIC SEALING SYSTEMS

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ABSTRACT

This paper shows and explains which visual failure analysis methods are meaningful and how they can be useful to analyse dynamic sealing systems. While most people think a scanning electron microscope (SEM) image of a sealing edge is always necessary, the presentation helps to judge which method is better suitable. This leads to an adjusted effort while costs and primarily time is saved. The result is a perfect analysis and the knowledge about the tribological function [1] or the failure mechanism [2], [3].

Keywords: Visual Analysis, Failure Analysis, Sealing Systems, Lip Seal, Shaft

INTRODUCTION

A dynamic “seal” is not a single machine component. A dynamic “seal” is always a complex system which consists of the four partners seal-element (lip seal, rod seal, linear wiper,…), the counterface (shaft, piston, rod, linear guides,…), the lubricant, the surrounding and the working conditions. To choose the best fitting seal it is necessary to know how the seal works and how the different partners influence each other. To show which visual analysis system fits best and how to do a visual failure analysis the sealing system radial lip seal is chosen.
To choose the best sealing system for the longest lifetime and for the most reliable system, it is important to know the failure mechanisms of the seals in the different applications. Some lip seals fail due to heavy wear with grooves at the sealing edge (Fig. 1) others due to heavy wear of the shaft caused by particles (Fig. 2).
Visual analysis complemented tactile analysis in the past, but now we have tools (3D, Laser, WLI,…) to do all analysis just visually, more exact and several times faster than ever before. But to use the right one at the right time, one must have the knowledge of their advantages.

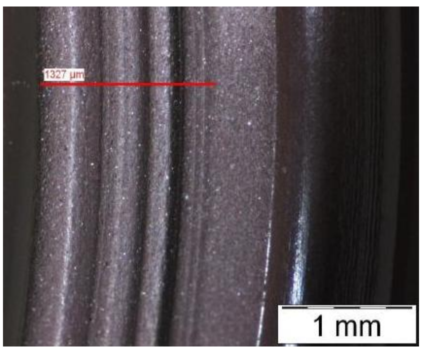


Fig. 1: Heavy wear and radial grooves at a lip seal due to bad lubrication

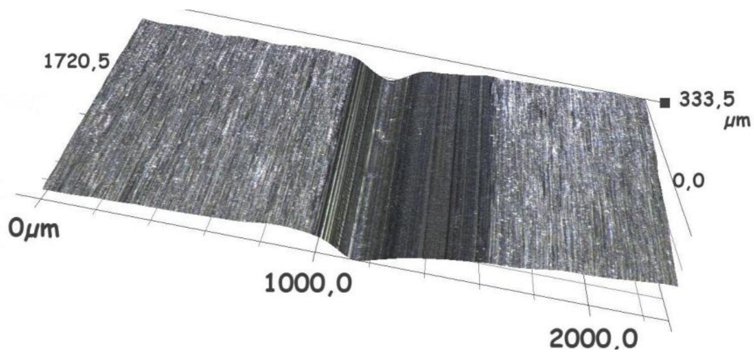


Fig. 2: Heavy wear of a shaft due to particles in the lubricant

FUNCTION OF ELASTOMERIC RADIAL LIP SEALS

The function of a radial lip seal (rotary shaft lip type seal) is based on the distortion of micro asperities of the soft elastomeric sealing edge while the shaft rotates. Due to different angles of the sealing edge at the oil side and the air side an asymmetric pressure is applied and therefore the distortion is also asymmetric. This results in “two micro pumps” beneath the sealing edge. The one on the oil side pumps oil in the contacting area of the sealing edge and the shaft. The other pumps the oil back to the oil side. Therefore the system is well lubricated, the temperature due to the friction is controlled and no leakage appears. This complex system works perfectly as long as the elastomeric sealing edge is not disturbed. The sealing edge has to look as illustrated in Fig. 4.

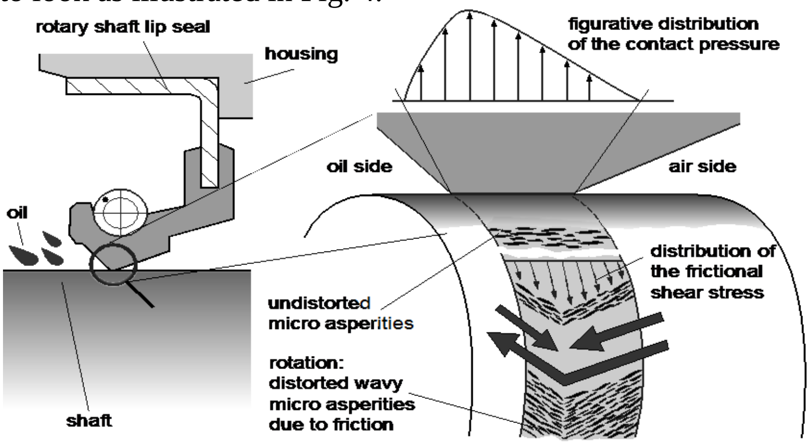


Fig. 3: Function of a radial lip seal system

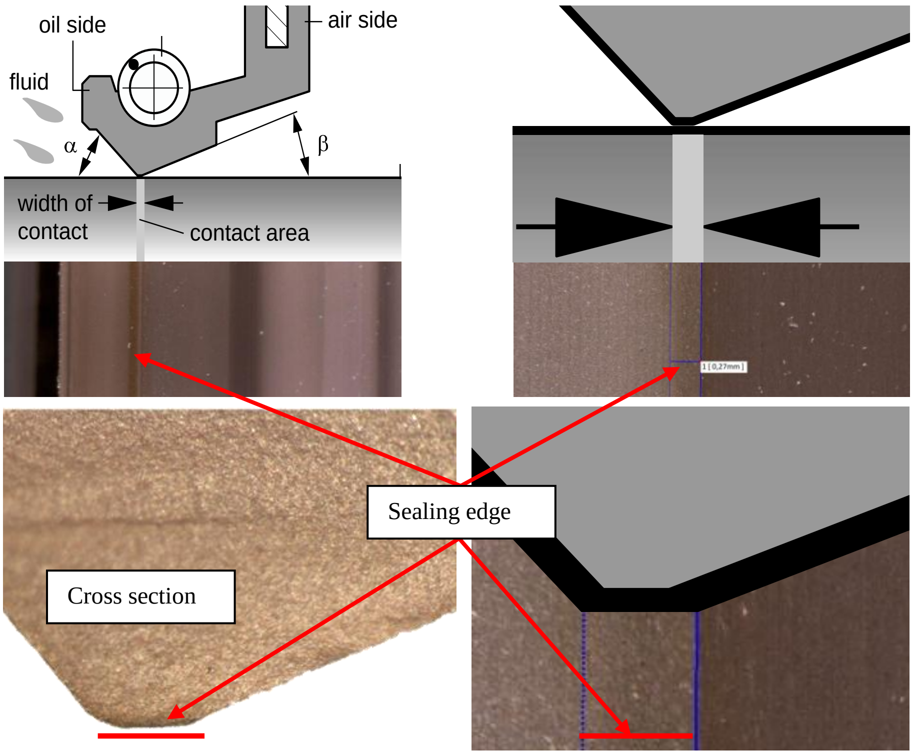


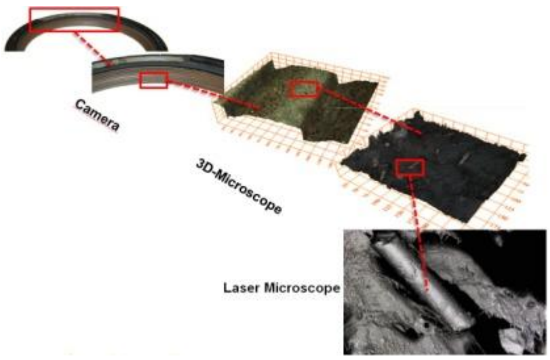
Fig. 4: Perfect “moderate and smooth worn” sealing edge

FAILURE MODES

The author presented different failure modes which are identified at the IMA in [2] and [3]. All of the named failure modes can be found in all areas of mechanical and automotive engineering. But in the field of radial lip seals there are just some general publications of failure analysis available, e.g. [4] and [5]. The pictures in [4] are used in a number of other publications and set the standard in the past, but there is no exact explanation how they appear, how they have to be analysed and how they can be prevented.

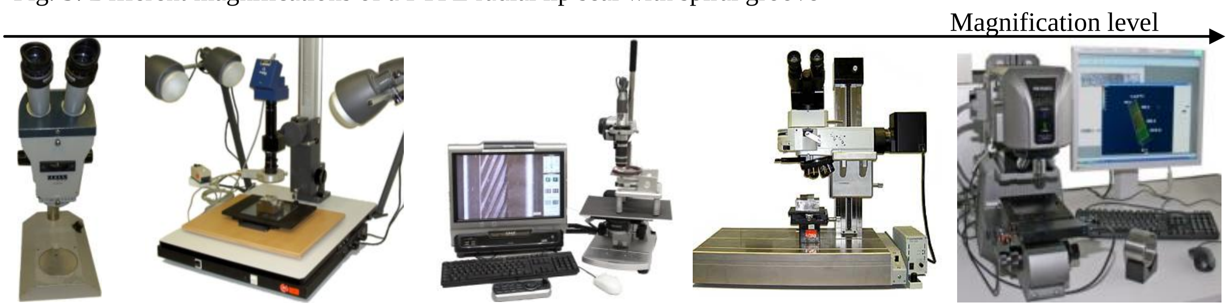
ANALYSIS METHODS

Which is the right method or device to analyse the different failure modes?
In Fig. 5 pictures of a PTFE radial lip seal in different magnifications are shown. The pictures start from an overview of the whole seal, includes single convolutions of the pressed spiral groove and the surface roughness and ends with the PTFE matrix with its fillers. In Fig. 6 some 2D-/ 3D-microscopes and in Fig. 7 some non contacting surface metrology and material characterisation devices are shown.



- If one wants to analyse a failure due to eccentricity of the lip, the camera picture would be helpful.
- If one wants to analyse wear on the surface of the seal, the 3D microscope picture would be helpful.
- And if one wants to analyse filler-characteristics a picture of a laser microscope or a SEM is required.

Fig. 5: Different magnifications of a PTFE radial lip seal with spiral groove



Stereo-microscope	Navitar Zoom Lens Jenoptik ProgResC14	Keyence VHX-1000	Olympus BXFM	Keyence VK9710 Laser Scanning Microscope

Fig. 6: Different visual analysis devices at the IMA (Institute of Machine Components)/ University of Stuttgart

FRT Microprof CHR150 Chromatic Aberation Sensor	Keyence VK9710 Laser Scanning Microscope	Bruker NPLEX-LA Whitle Light Interferometer	SEM + EDS Scanning Electron Microscope with Energy Dispersive X-ray Spectroscopy

Fig. 7: Different analysis devices at the IMA (Institute of Machine Components)/ University of Stuttgart
Surface metrology and material characterisation

Example:

If one would use a SEM image (Fig. 9) with a very high magnification and therefore a small field of view (FOV) while having a huge depth of field (results in a sharp picture) to analyse the sealing edge shown in Fig. 9, he could miss the axial scratches. Therefore he would find a perfect sealing edge instead a destroyed and discoloured sealing edge with axial scratches in the hardened surface. This confirms how important it is to use the right device for the respective goal.

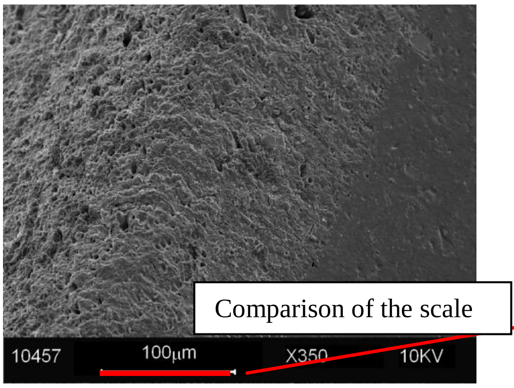


Fig. 8: SEM image of a perfect smoothly worn small section of the sealing edge of Fig. 9

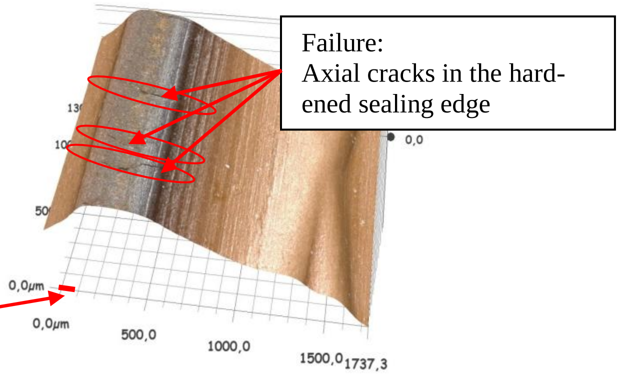
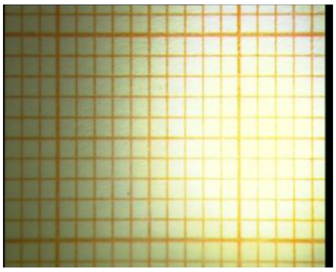


Fig. 9: 3D-view of a hardened and discoloured sealing edge with axial scratches

PREAMBLE

Many students and engineers store and publish their pictures without any scale or burned-in measurements. Others think it is enough to note and publish the magnification factor. Mostly they even do not know that the magnification factor of the microscope is the product of the magnification of the objective and the magnification of the additional lenses. They often just note the displayed magnification of the objective.
BUT:
When the pictures are printed or viewed on the screen the magnification of the real object differs with the paper size or the screen size. An example is given in Fig. 10. Therefore it is absolutely required to burn-in a scale in every "failure analysis picture". This scale is independent from the magnification of the displaying medium.



Displayed magnification objective: 0.58
Field of view: ~ 18 X 12 mm

Example:

Size on DIN A4 printout:
Field: ~ 42 X 33 mm
➔ magnification: 2.5

The displayed magnification of the objective differs from the magnification of the real object to the printout

Fig. 10: Example: Difference of the displayed magnification of the objective and the displaying medium

PHYSICALLY BASED ISSUES OF VISUAL FAILURE ANALYSIS

Some problems for a proper failure analysis of dynamic lip seals are based on physical properties and their limitation. A simplified schematic explanation is given in Fig. 11. The problems are the limited

1. Field of view: The area which can be observed. When the magnification is too high and therefore the field of view is too small the interesting areas are hard to find.

2. Depth of field: The depth in which a sharp view is possible. This is no problem on flat surfaces like linear guides but it is a big problem on seal rings.
3. Working distance: If the specimen is too big for the device so that it does not fit beneath the working distance it cannot be observed.
4. Available space on the stage or the size of the working chamber (e.g. SEM).

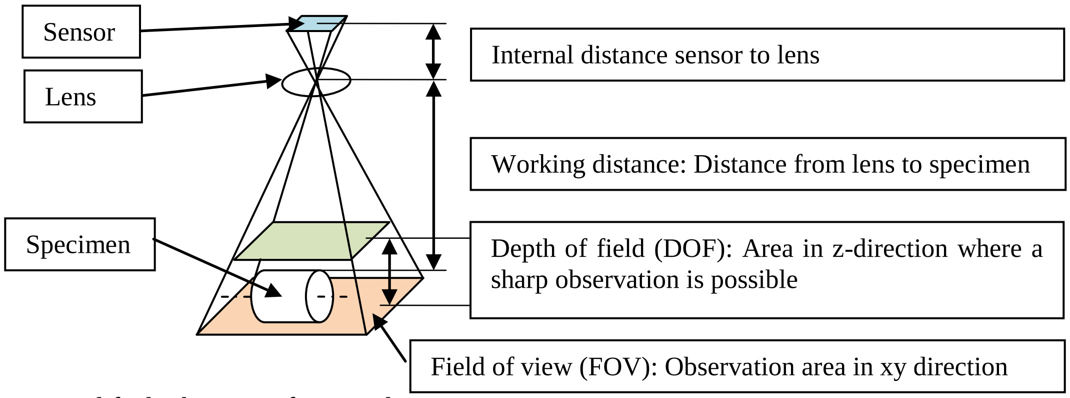


Fig. 11: Simplified schematic of a optical system

HANDICAPS

The biggest handicap for an easy and fast analysis is the fact that dynamic seal elements like radial lip seals, rod seals and others are formed like a ring. Therefore the interesting tribological contact areas (sealing edge) in the inside of the ring cannot be analysed from the top (Fig. 12). Mostly the optical system is much bigger than the inner diameter of the ring and does not fit inside the ring. So the sealing edge cannot be observed directly and has to be mounted angled (Fig. 13) or the objective itself has to be angled (Fig. 14). Both methods work well with bigger seals but will not work with smaller seals because the working distance can be too short to observe the sealing edge (the area of observation) with a sharp view.

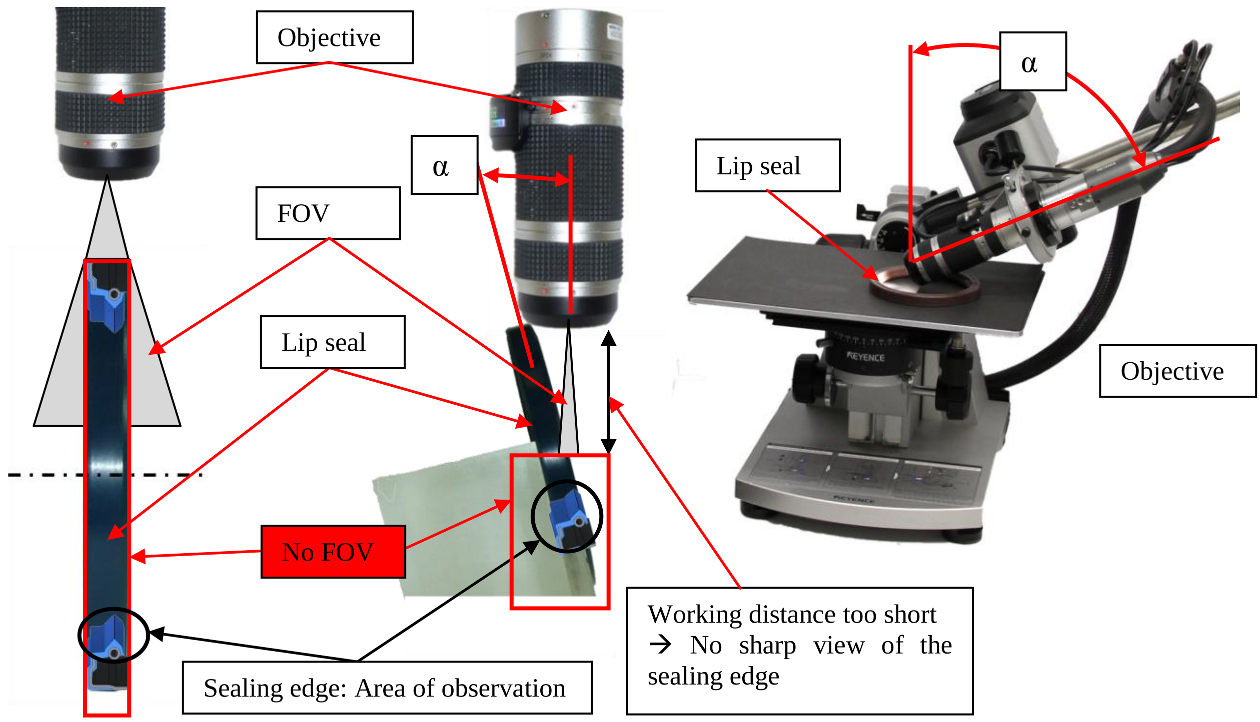


Fig. 12: Vertical lip seal Fig. 13: Angled lip seal Fig. 14: Angled microscope – horizontal lip seal

PROCEDURES AND ESSENTIAL DEVICES

In cases where the seal element cannot be observed it has to be cut. This method has several disadvantages:

1. It is not easy to cut the soft elastomer without modifying or deform it.
2. The seal is destroyed and cannot be used for further tribological analysis.
3. It cannot be assured that the interesting part of the sealing edge is chosen.
4. The macro-geometry is changed, because the ring with its spring is cut.

A cross section of a cut elastomeric radial lip seal is shown in Fig. 15. It is helpful to fix the specimen with modelling clay. With this method the sealing edge or the cross section can be observed with all kinds of visual devices, because the specimen is small and the working distance can be short. An advantage of this method is that the sealing edge can be manually shifted and rotated. Therefore it can be analysed from different angles and at different positions (Fig. 16). Additionally it can be easily deformed. This method is used to find cracks, opened channels and scratches as visualised in Fig. 17.

Fig. 15: Cut section of a radial lip seal

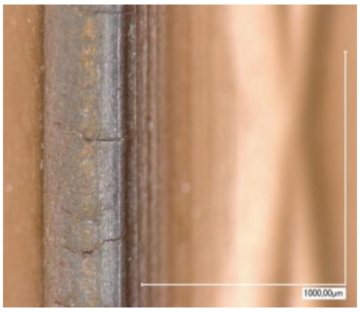


Fig. 16: Cut section of a hardened and discoloured sealing edge with axial scratches

Fig. 17: Deformed section of the sealing edge (Fig. 16) with opened scratches

When the mounted geometry (and/ or the wear width and depth) have to be analysed the seal can be cast in a mould with resin as in Fig. 18. After hardening, the mould can be cut and the surfaces can be polished. With this method the seal is not deformed and it can be analysed like it was mounted in the real application. This method can be also used for unmounted seals. When the unmounted geometry (and/ or the wear width and depth) have to be analysed a very easy and fast method can be applied. The whole lip seal with the sealing edge can be mould with liquid or paste-like casting compound (Fig. 19). This method is a non-destructive method which is a huge advantage if further investigations have to be done.

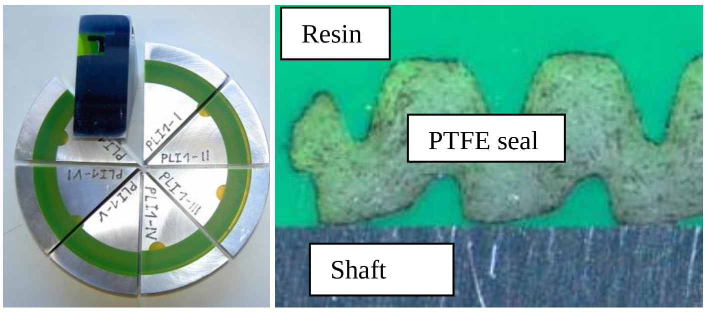


Fig. 18: Eight cut cross sections of a PTFE radial lip seal cast in a mould with resin

Fig. 19: Moulding with liquid (blue) or paste-like (green) casting compound

An almost perfect method to analyse a seal is to use a mirror or a prism. In Fig. 20 the Seal Observer with a moveable mirror and 2 arrestors for the seal ring is shown. With the help of the arrestors the seal can be rotated while the distance to the mirror and therefore the working distance to the lens remains stable. A sharp picture around the whole circumference is guaranteed and no failure is missed.
An advanced method is to use a glass hollow shaft. In the Mounted-Seal Observer (Fig. 21) the seal is mounted on the glass hollow shaft and can be observed with the help of a prism. The glass hollow shaft with the mounted seal can be rotated while the distance to the prism and therefore the working distance remains stable. With this method the seal can be analysed as it was mounted in the real application. As in all microscopic applications it is hard to illuminate the specimen sufficiently. To solve this problem the IMA applied fibre optics parallel to the path of rays, which can be dimmed separately. The fibre optics are lightened by a cold light.

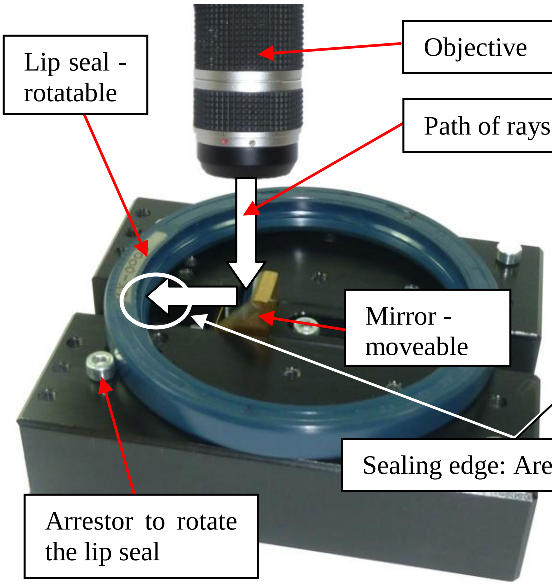


Fig. 20: Seal Observer with mirror and rotatable seal

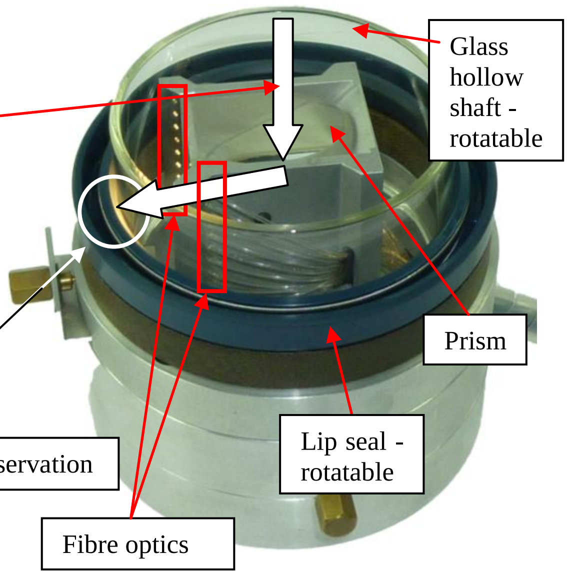


Fig. 21: Mounted-Seal Observer with prism and rotatable glass hollow shaft

Before one can use these devices it is necessary to understand the difference in both methods and their influence on the result of the failure analysis.

EXCURSION

In Fig. 22 the possible states of an elastomeric radial lip seal are presented.
1: New condition, unmounted
2: New condition, mounted on a shaft with a contact width of approximately 0.1mm.
3: Worn condition, mounted, sealing edge width of approximately 1mm
4: Worn condition, unmounted, worn sealing edge width of approximately 1mm

The unmounted sealing edge has a smaller inner diameter as the shaft (1) and will be widened during the assembling on the shaft (2, 3). After disassembling the worn sealing edge contracts to its original shape (4). At the unmounted state the worn area/ contacting area of the sealing edge is no more perpendicular to the housing of the seal and therefore no more perpendicular to the microscopic view.

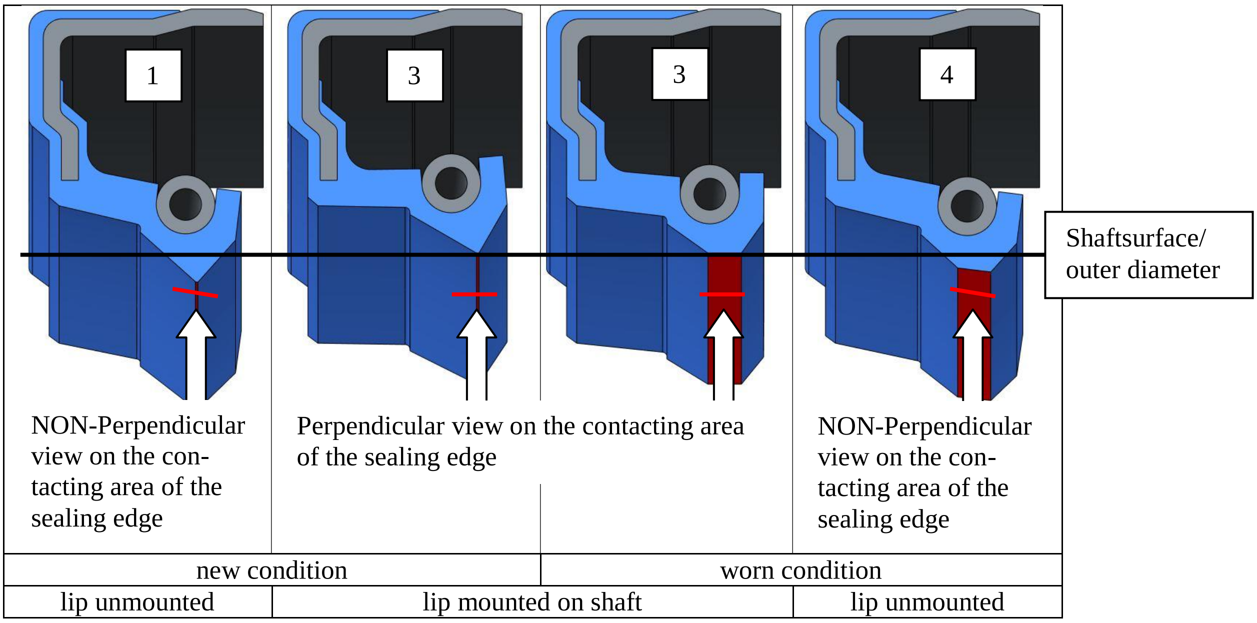


Fig. 22: Possible states of a radial lip seal

With this knowledge it is possible to decide if the seal should be analysed in mounted or unmounted position:

- When the seal is analysed with the Seal Observer the condition of the uncleaned sealing edge with all particles and oil can be observed correctly. This is essential if the real failure has to be found. The disadvantage is that the unmounted sealing edge is contracted to its original shape and the contacting area on the sealing edge is not perpendicular. This can lead to unsharp pictures because the angled surface is not completely in the depth of field and therefore the analysis is much harder and more time consuming because the different areas of the view have to be focused separately.
- When the seal is analysed with the Mounted-Seal Observer on the glass hollow shaft the contacting area of the sealing edge can be observed in the “real position” as in the application and the seal can be easily rotated. Additionally the view is perpendicular to the contacting area. Therefore this area is completely in the depth of view. This is also comparable to the resin cross sections were also the real situation is applied. A huge disadvantage is, that the seal can only be analysed cleaned. If an uncleaned seal is mounted the potentially clinging wear particles, the oil coal and the oil are wiped off and the real failure mode cannot be found.

BEST PRACTICE

To avoid all problems mentioned so far we developed a device where the problems do not appear. We named this device coherently IMA Seal Observer (Fig. 23).

The seal seats on a plate. With the help of two arrestors the seal can be rotated easily. A prism with 20 separately dimmable LEDs is inside the seal ring (Fig. 24). To adjust the working distance to the objective and adjust the view, the prism is moveable in height and length. Additionally the plate can be tilted. With this method the sealing edge can be perfectly adjusted to get a perpendicular view on the contacting area. The distance from the prism to the sealing edge remains constant while rotating. The advantage of the angled plate against the Unmounted Seal Observation Device (Fig. 20) is illustrated in Fig. 25 and 26. The pictures with the angled plate compared to the horizontal plate are shown in Fig. 27 and 28.

With the IMA Seal Observer the sealing edge can be observed completely around the circumference without focusing and changing any parameter in different magnifications.

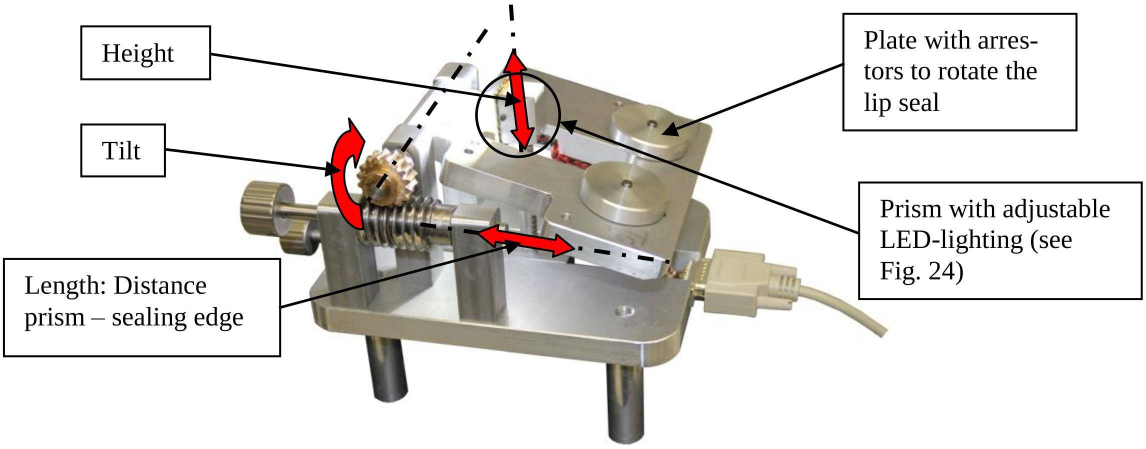


Fig. 23: IMA Seal Observer

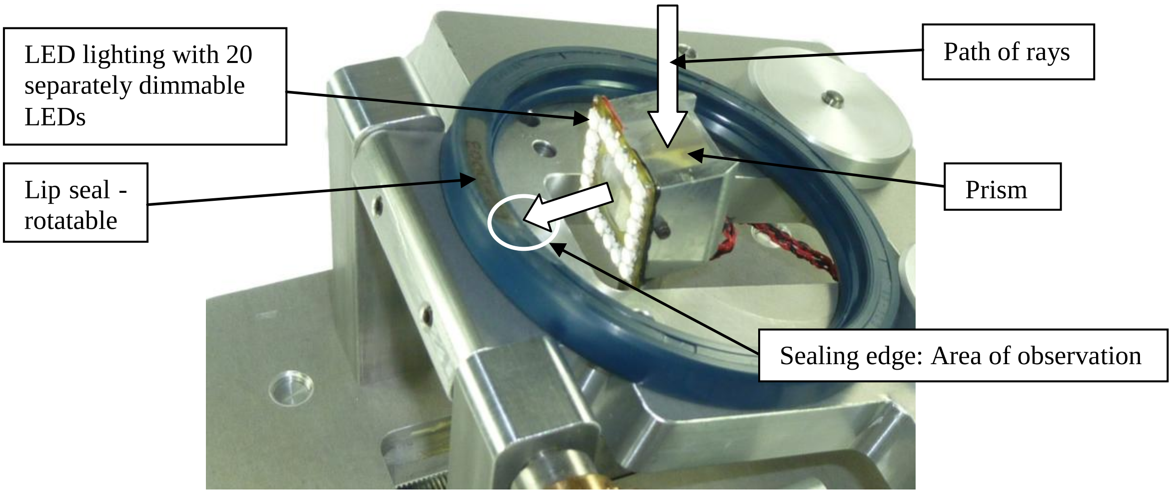


Fig. 24: Prism with adjustable LED-lighting and rotatable seal

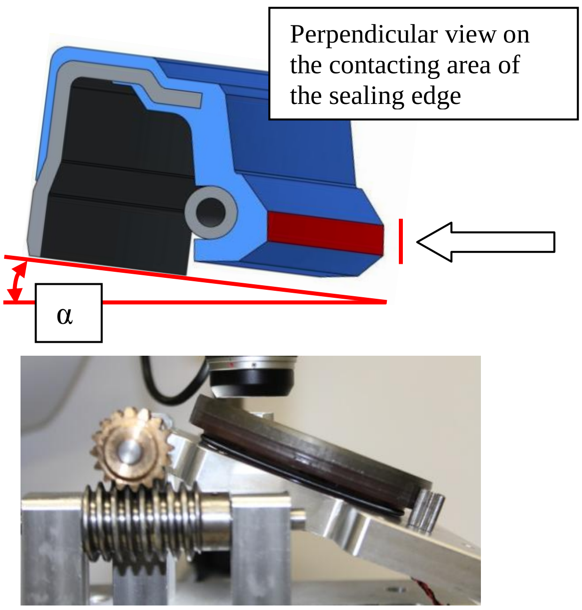


Fig. 25: Base plate tilted

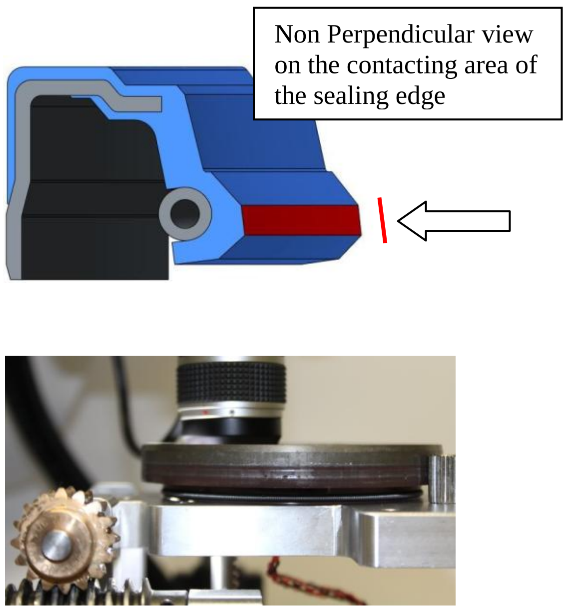


Fig. 26: Base plate horizontal [comparable to the Seal Observer (Fig. 20)]

Perpendicular view on the contacting area of the sealing edge

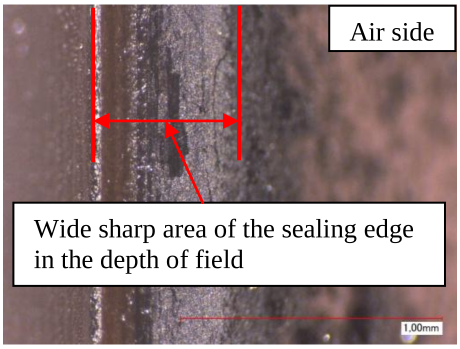


Fig. 27: Sealing edge/ tilted base plate

Non Perpendicular view on the contacting area of the sealing edge

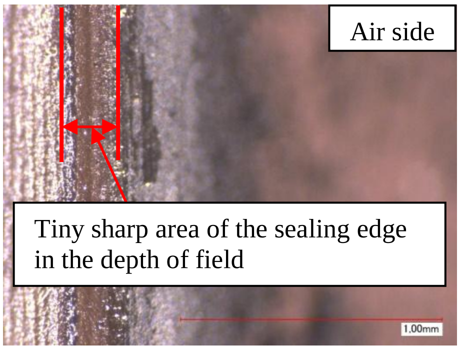


Fig. 28: Sealing edge/ base plate horizontal

FOCUS STACKING AND 3D IMAGING

In some microscopes the so called focus stacking technology is applied. Those microscopes have motorised z-axis where the focus can be adjusted by the motion of the objective. The software takes a picture in each z-level and separates the sharp areas. Those sharp areas are used to build up one sharp picture. The result is shown in Fig. 29 and Fig. 30 in comparison to the single focus pictures.

HINT: Although one can get a sharp picture even with a non-perpendicular view, it is advisable to tilt the seal to a perpendicular view. This step is always necessary because the measurement is only acceptable in a perpendicular view. The correct measurement of the sealing edge (with oil coal) displays a contact width of 0.36 mm while the measurement in the non perpendicular view displays an incorrect width of 0.33 mm.

➔ Measurements in pictures are only allowed perpendicular in the sharp area within the depth of view!

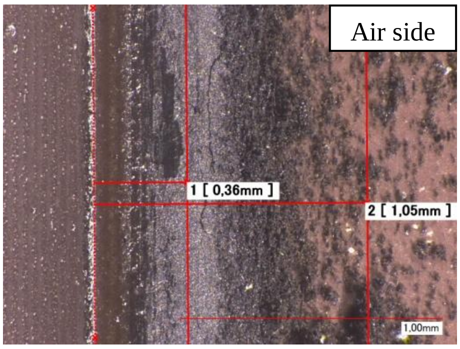


Fig. 29: Sealing edge/ tilted base plate with focus stacking

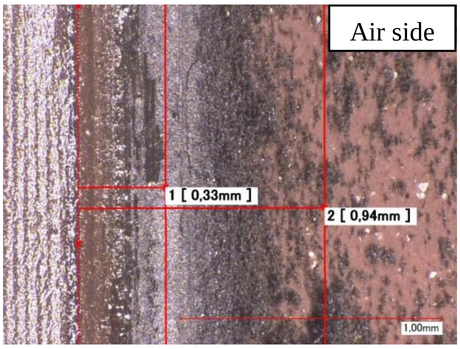


Fig. 30: Sealing edge/ base plate horizontal with focus stacking

With the knowledge of the height of each sharp area the software can also build up a 3D picture (Fig. 31). Those 3D pictures are rotatable and scalable.

➔ Measurements in 3D pictures are only allowed with the original software!
Otherwise the values are incorrect.

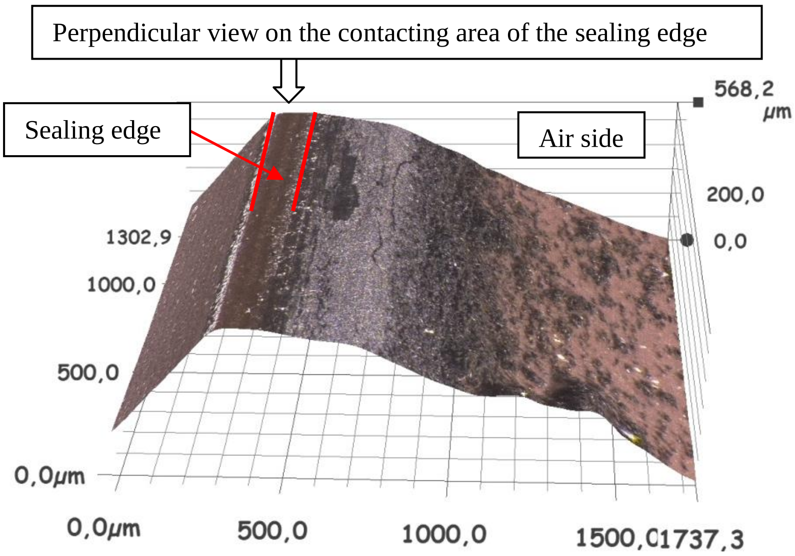
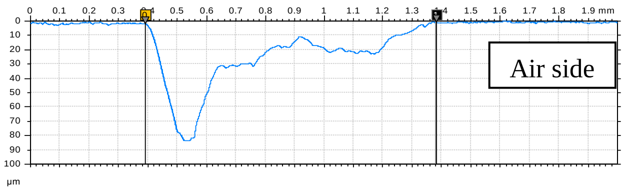


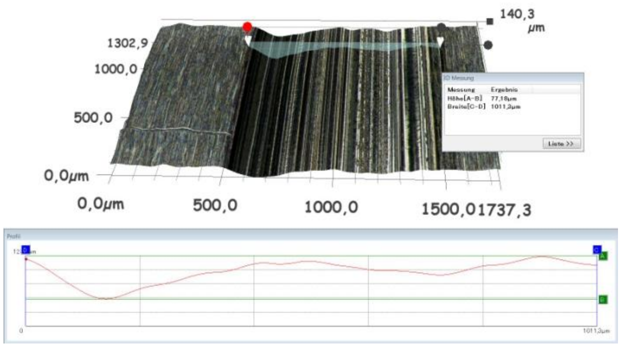
Fig. 31: 3D picture of the Sealing edge/ tilted base plate with focus stacking

Measurements of the depth are a good orientation for the user but no correct measurement. The data of the z-axis is just a value from the moveable objective at every sharp depth level.
In Fig. 32 a tactile measurement, a focus stacking "measurement" and a laser microscope measurement (very exact in z direction) at the same position of a shaft are compared. As clearly visible the length is identical with every method but the measurement of the depth is incorrect in the focus stacking picture.

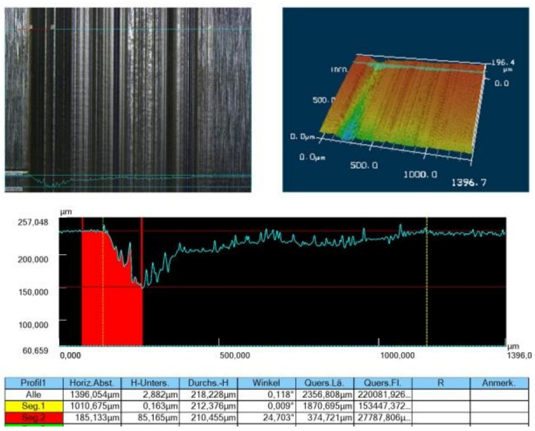
➔ Measurements of the depth are more exact with a tactile measurement device or a laser microscope measurement than with a focus stacking system.



Wear track on shaft measured tactile:
Width: 0.99 mm; Depth: >80µm [outside range]



Wear track on shaft measured with focus stacking:
Width: 1.01; **<u>Depth: 77 µm ➔ Not deep enough!</u>**



Wear track on shaft measured with laser microscope:
Width: 1.01 mm; Depth: 85µm

Fig. 32: Comparison of different analysis methods

OTHER MEASUREMENT DEVICES

The other mentioned analysis devices like the chromatic sensor or the white light interferometer are not suitable for failure analysis of the sealing elements because they do not deliver sharp coloured pictures. Instead they are very useful for the analysis of the shaft surface, i.e. analysing roughness parameters, the surface microstructure or the wear profile.

The big advantage of a scanning electron microscope (SEM) is the huge depth of view. Nevertheless it is not suitable for a standard failure analysis because the field of view is too small and the seal rings have to be cut. Another disadvantage is the fact that it is not very easy to use. A SEM could be used to analyse a special spot following a standard visual failure analysis.

SUGGESTION FOR A VISUAL FAILURE ANALYSIS OF A SEAL

1. Use the IMA Seal Observer
2. Tilt the plate so that you have a view perpendicular on the sealing edge
3. Take pictures of the uncleaned seal so that no information is lost
4. Take a lot of pictures around the circumference at different magnifications
5. Clean the seal element
6. Take a lot of pictures around the circumference at different magnifications
7. Measure the radial force
8. Now every other method (e.g. with a glass hollow shaft) can be done additionally

SUMMARY

To choose the best suitable method, the essential devices and the measurement equipment for a failure analysis is not easy. It is very important to choose the right one at the right time. Mostly one single system is not adequate and a good combination leads to the best result. For scientific analysis it is understood at the IMA that we compare 3 tactile measurements of a wear track on a shaft with three visual analyses. If the results have not to be that exact, the modern visual analysis methods are much faster and cheaper and deliver perfect 3D pictures.

The knowledge of the right method to analyse failures is necessary to identify the failure at the machine component and therefore the root cause of the fail of the whole machine.

REFERENCES

(1) Bauer, F; Haas, W.: *Radial Lip Seals – Overview and Function*, 18th International Colloquium Tribology, Ostfildern-Nellingen, 10.-12. Januar 2012, Book of Synopses 2012, W. J. Bartz (Hrsg.) - TAE Esslingen, S. 155, ISBN 3-924813-97-3

(2) Bauer, F.; Haas, W.: *Failure Analysis of Elastomeric Lip Seals*, Proceedings, ICEFA 5, The Hague, Netherlands, July 2012

(3) Bauer, F.; Haas, W.: *Blisters on Radial Lip Seals - A More and More Frequent Failure Mode*, Proceedings, 11th EDF/Pprime Workshop, Poitiers, France, September 2012

(4) Prem, E.; Vogt, R.: *The Simmerring, Basics for preventing damage*, Freudenberg Simrit GmbH& Co. KG

(5) Dinzburg. B.: *Ölkohleaufbau bei dynamischen Wellendichtringen*, evolution, evolution.skf.com, 4/2000