EXPERT KNOWLEDGE
FAILURE ANALYSIS
OF ELASTOMER COMPONENTS

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Extrusion –
The Sealing Gap as the Enemy of the Seal

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1. Classification and Frequency of the Damage Pattern

Of the four main damage mechanisms, extrusion is assigned to the third main group:

1. Mediums
2. Temperature / Aging
► **3. Mechanical / Physical Effects**
4. Manufacturing Defects

The third main group can be divided into three subgroups: assembly errors, incorrect installation space and physical overloading due to operating conditions. Gap extrusion belongs to the last subgroup and is a frequent and well-known failure cause in hydraulic systems. Further damage mechanisms from this subgroup are abrasion, explosive decompression or blow-by and flow erosion.

2. Technical Background Knowledge on the Damage Pattern

This cause of failure is often described in literature and on the Internet, presumably because, on the one hand, it has a very distinct and clearly identifiable damage pattern and, on the other hand, because it frequently occurs in hydraulic systems, which traditionally has been dealt with in systematic analyses of seal damage at very early stages.
This error is usually referred to in English as "extrusion", but sometimes the term "gap extrusion" or "nibbling" is also used.

Rubber behaves like an incompressible liquid. As the pressure rises, a seal adapts more and more to its installation space until it is finally pressed into the low-pressure gap. This process is known as extrusion. The O-ring or the hydraulic seal is "peeled off - or nibbled on by the breathing of the machine parts"[1]. Due to the high pressure, more and more new material is pushed into the gap, so that sometimes long extrusion flags are produced, which can be many times longer than, for example, the cord thickness of an O-ring. The "material pressed into the gap is unable to withstand the internal stresses and is overloaded and deformed by tensile forces, tears, extrudes and crumbles"[2].
The "nibbling" occurs because the gap closes abruptly after pressure relief and the material extruded into the sealing gap cannot retract quickly enough and is sometimes sheared off. This problem occurs mainly with O-rings and hydraulic seals and depends on a number of factors. At least two of the following causes are always responsible for this type of damage, but the damage can sometimes be remedied by changing just one parameter.

For the damage analysis of the extrusion, four areas must be examined:

- Pressure
- Constructive boundary conditions
- Sealing material
- Temperature

In order to determine the exact cause of damage, a more differentiated consideration and subdivision of these four areas is still necessary in most cases. This is the only way to find and implement effective and sustainable remedial measures.

2.1 Pressure

In literature, only system pressure is usually described as a problem, but the pressure rise rate and drag flow pressure also have an influence on gap extrusion that should not be underestimated.

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[1] translated from PARKER Hannifin GmbH (Hrsg.): O-Ring Handbuch, November 2005, P. 166
[2] translated from SCHRADER, Klaus: Hydaulik-Dichtungen Teil II: Schadensbilder, -ursachen, -vermeidung in o+p Ölhydaulik und Pneumatik, Heft 5, Band 26, 1982, P. 358

2.1.1 System Pressure

This parameter has the most important influence on the extrusion. However, the system pressure is usually fixed at the beginning of a design, so that constructive or material-related ways have to be found to deal with the given pressure without increasing the manufacturing costs (due to very narrow tolerances). From an experimental point of view, the critical pressure with regard to extrusion can be represented as the buckling point of the course of the displaced gap volume over the pressure (see **Fig. 1**).
With typical material harnesses of 70 Shore A or higher and with the usual gap dimensions of max. 0.3 mm, the damage mechanism of the gap extrusion does not occur under 50 bar pressure (see **Fig. 2**). "The process [of gap extrusion] is furthered by the fact that the pressure p expands the cylinder tubes so that the gap is enlarged. As the pressure is reduced and the friction forces are exerted, the reversal of movement causes the seal material to rupture"[3]

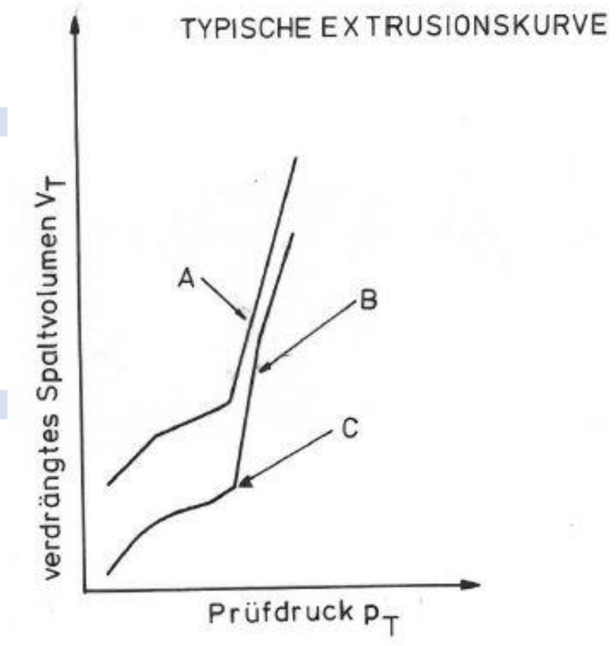

Fig. 1: Measurement of the volume moved from the O-ring into the sealing gap as a function of the test pressure: curve A stands for the elastic deformation and curve B for the permanent deformation of one and the same material.
The kink point C in the curve stands for the bursting of the surface of the O-ring, which is the beginning of the critical extrusion.[4]

2.1.2 Pressure Rise Rate

The viscoelastic behavior of elastomers means that the resistance of the material to deformation is not only dependent on the degree of deformation, but also on the rate of deformation and the temperature (see 2.4). This means that the same pressure, if it rises faster, also produces higher line or surface pressures at the sealing gap. " Hard" pressure surges involve a considerably higher risk of seal failure (see **Fig. 7**) than "soft", meaning slow

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[3] translated from SCHRADER, Klaus: Hydaulik-Dichtungen Teil II: Schadensbilder, -ursachen, -vermeidung in o+p Ölhydaulik und Pneumatik, Heft 5, Band 26, 1982, P. 358

[4] RICHTER, Bernhard: Dichtungen sicherer machen in: KEM Konstruktion, Elemente, Methoden Technologische Informationen für Konstruktion und Praxis; 22, Heft 1, 1985, S. 78-80

pressure changes. These "hard" pressure surges can be caused by sudden loads (e.g. on forklift trucks or in rolling mills) or by very fast switching of valves, such as digital valves. Such influences are difficult to calculate and predict. For this reason, particularly in critical applications, preventive measures are taken to protect the seal against extrusion (hard materials, small gaps, small edge radii and the use of support rings). When compressible gases are sealed, the risk of extrusion is significantly lower compared to hydraulics because gases cushion hard pressure surges more.

2.1.3 Drag Flow Pressure

In hydraulics there is the phenomenon of drag flow. Despite intact seals, a drag flow can cause leaks. Drag flow causes unwanted pressure build-up in the sealing system.
"The viscous medium in the gap, almost always a Newtonian liquid, is subjected to shear stress by the relative movement between the rod and the guide. The boundary layer in contact with the rod will move at the speed of the rod, while the boundary layer at the guide bushing remains at rest with the guide bushing."[5]
"The oil dragged along by the rod is wiped off and sealed by the seal, thereby building up a pressure - the so-called drag pressure, pSch. A backflow then occurs in the guide gap (...) and pressures can occur upstream of the seal which are many times higher than the system pressure"[6]. This high increase in pressure can result in a gap extrusion.

2.2 Constructive Boundary Conditions

Of course, the determination of the gap dimension is the most important design influencing factor. However, also a correct execution of the edge radii, groove recesses and a sensible layout of the O-ring cord thickness must not be ignored. In addition, dynamic seals are much more susceptible to the damage mechanism of extrusion than static seals.

2.2.1 Clearance

Usually there are always gaps between a piston and cylinder or between a plug-in and a housing part. In static applications, reducing the gap to a minimum is primarily a cost issue; the closer the required tolerances are, the more expensive production becomes.
Dynamic sealing applications even require a certain sliding gap. This gap is usually larger than the ideal value for the seal.[7] In dynamic applications, the cylinder can also be expanded under pressure. Here, too, the costs of solving a problem play a major role, since stiffening the components usually involves more material input. The consideration of this effect of cylinder expansion is often forgotten or ignored when designing the gasket.
In fluid technology, a typical sealing gap in the piston diameter range from 20 to 100 mm is 0.07 to 0.13 mm, e.g. in accordance with ISO 3601-2.[8] (H8/f7).

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[5] translated from HÖRL, Ernst: Dichtungen in hydraulischen Geräten - Grundlagen der Dichtungstechnik, Schadensursachen und Auswahlkriterien zur richtigen Festlegung von Dichtstellen in: STREIT, G. (Hrsg.): Elastomere Dichtungssysteme, expert-Verlag, Renningen, 2011, S. 415
[6] translated from Ebd., S. 417
[7] PARKER Hannifin GmbH (Hrsg.): Dichtungshandbuch, August 1999, S. 111
[8] ISO 3601-2: 2016-07 Fluid power systems- O-rings- Part 2: Housing dimensions for general applications

As a matter of principle, when designing the correct material hardness at a given pressure depending on the gap dimension the theoretically maximum possible diameter clearance should always be used as a basis, that is the theoretically maximum eccentricity. Extrusion always begins at the point of the largest sealing gap (see **Fig. 8**). Only when the concentricity of the components to be sealed has been ensured by an additional guide can half the diameter clearance be used as the sealing gap.

2.2.2 Edge Radius / Groove Recess

The susceptibility to gap extrusion is essentially influenced by the edge design of the groove. ISO 3601-2 specifies an edge radius of 0.2 ±0.1 mm for rod and piston installation and 0.1 - 0.05 mm for flange gaskets. In principle, an edge radius of 0.05 to 0.1 mm corresponds to the ideal case. This is particularly useful if not only the pressure head is in a critical range, but also high pressure rise rates occur since sharp edges show their damaging effect much faster. A cyclical pressure load at a frequency of 0.1 to 1 Hz is rather considered to be low, whereas a pulsating pressure at a frequency of 10 to 100 Hz is rather considered to be high.

When designing the groove recess, it must also be ensured that the edge radius merges with the groove flank without discontinuity, otherwise damage to the O-ring may occur in the event of hard pressure surges. Of course, this also applies for 45° phases as edge break instead of the required radii.

If the groove recess is sharp-edged, the O-ring or seal will be peeled (see **Figs. 5** and **9 to 11**). Typical for this cause of failure is a strikingly strong damage pattern and a clean straight start of the peeling process.

2.2.3 O-Ring Cord Thickness

In older documents from seal manufacturers[9], empirically determined diagrams can be found in which the cord thickness appears as a parameter when designing extrusion-proof O-rings. During intensive tests at Parker Hannifin Seal Group[10] (R and D), a significant influence of the cord thickness on the extrusion resistance could not be confirmed, which is why it does not appear in the Parker diagram (see **Fig. 2**). However, it should be mentioned that this influence certainly exists, but only in the case of untypically large sealing gaps, which is an untypical ratio of gap to cord thickness. If this ratio is < 0.1, it is assumed that the cord thickness has no significant influence on the start of gap extrusion. Such a beginning of gap extrusion is a design criterion which is understood to mean the bursting of the O-ring at the sealing gap that is to be avoided.

If, on the other hand, you only consider the time until a leakage occurs at a given pressure and sealing gap, which means the final failure, it is certainly advantageous to use larger cord thicknesses.

In general, larger cord thicknesses are to be preferred in applications susceptible to extrusion.

2.2.4 Influence of Breakaway and Friction Forces in Dynamic Applications.

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[9] z.B. Prädifa Dichtungshandbuch-Handbuch pdf 14110845-D

[10] KOSTY, John: Extrusion resistance of elastomers and plastic materials in: ASME-Papers, Reportnr. 84-Pet-9, 1984, S. 1-7

In dynamic sealing applications, compressive and frictional forces may be directed in the same direction to the seal, significantly increasing the stress on gap extrusion (see **Figs. 11 and 12**). This is why the Freudenberg catalogue[11], for example, distinguishes between static and dynamic applications in design diagrams to prevent gap extrusion. The maximum pressures still permitted without the use of support rings are considerably lower in dynamic applications.

2.2.5 Other Constructive Boundary Conditions

"Ovality between metal parts, as usually found in hydraulic cylinder applications"[12] can also promote gap extrusion.

The wear of the metal parts during operation can lead to inadmissible gaps, which in combination with an aged O-ring can lead to gap extrusion.

2.3 Sealing Material

Literature usually only describes the important influence of seal hardness. However, hardness is only an insufficient indicator for the more influential deformation resistance or stiffness of a gasket. Moreover, the base polymer and the chemical resistance of a compound have an important influence on its extrusion resistance.

2.3.1 Sealing Hardness

The stiffer a gasket is, the more resistance it provides against gap extrusion. But the hardness provides only inaccurate information about the stiffness of a material (see explanations under **2.3.2**). Since in practice, however, comparable test values for the stiffness of an elastomer compound are rarely available, the widely used hardness is used as a guide.

Large gasket manufacturers offer their customers diagrams that can help to design an extrusion-resistant gasket. The following Parker diagram (**Fig. 2**) is widely known by users and does not consider cord thickness but only operating pressure and material hardness. With these two values, the designer can determine the maximum permissible gap. This determined value represents the sum of the two gaps in the central position of the cylinder or the largest gap in the completely eccentric position of the piston (= total diameter clearance).

The following diagram was created for relatively small cord thicknesses, so that applications with the less sensitive and larger cord thicknesses are also safely covered.

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[11] Freudenberg Dichtungs- und Schwingungstechnik, Standard Katalog-Technische Grundlagen 419 137-0996 D Page 239

[12] translated from CZERNIK, D.E.: Gaskets Design, Selection and Testing, McGraw-Hill, New York, 1996, P. 217

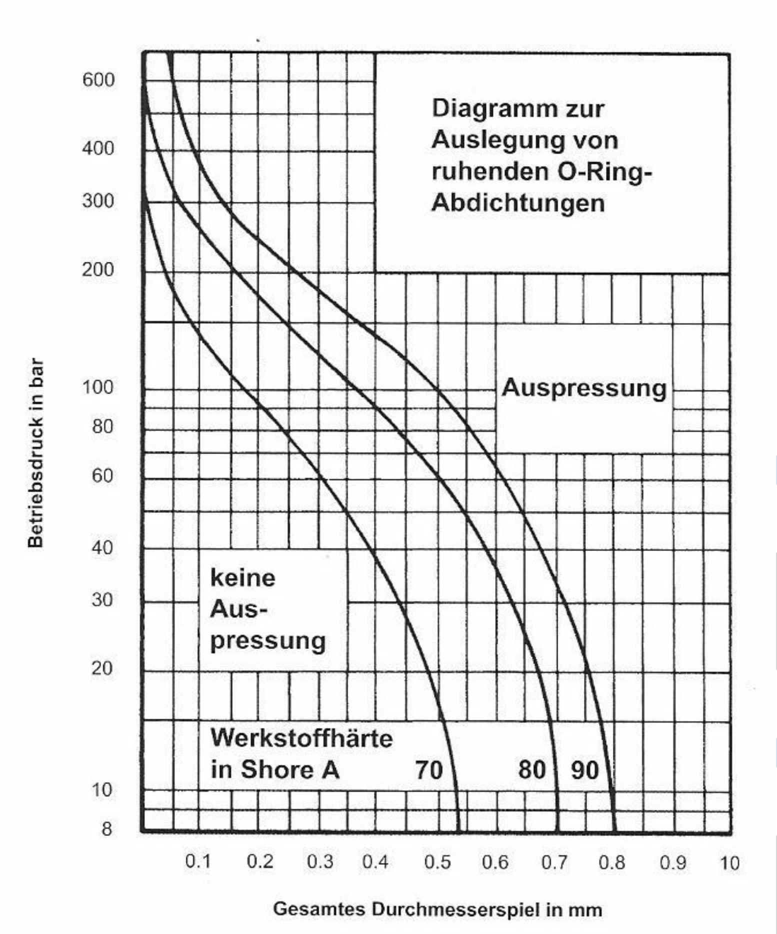

Fig. 2: Diagram for the design of statically used O-rings: Determination of the max. permissible sealing gap at a given system pressure *(The diagram is based on 100,000 cycles at 1Hz and applies to temperatures up to 70°C. With VMQ and FVMQ O-rings, the determined gap width is halved. Possible expansions of the cylinder are not taken into account)* [13]

2.3.2 Deformation Resistance of the Seal (Strength, Module)

Since hardness is widely known and simple to measure, it is often used to give an indication of the stiffness of an elastomer material. However, this is not so easy. "Although both the hardness and the tensile-stretch diagram (tensile test) indicate something about the stiffness of an elastomer, they are actually two essentially different types of deformation. Tensile strain measurements involve large deformations of the whole mass, whereas hardness tests involve only small deformations. Even if hardness and stiffness (represented by a tensile strain diagram) would have a better correlation, the generally given fluctuation range of +/-5 hardness points in Shore A measurement would already correspond to a scatter range of approx. 15 to 20% in stiffness, and even significantly more in hard materials (> 80 Shore A)".[14] Especially in the search for extrusion-resistant materials, which are generally in the upper hardness range, an understanding of these correlations is very important.

"For example, the hardness values on O-rings provide only rough indications of resistance to gap extrusion, while further valuable indications of resistance can be derived from a tensile test using stress values and strength values."[15]

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[13] PARKER Hannifin GmbH (Hrsg.): O-Ring Handbuch, November 2005, S. 162

[14] SMITH, L.P: The Language of Rubber, Oxford, 1993, P.12

[15] translated from BLOBNER, U.: Fachwissen Prüfverfahren für Elastomere: 1915 – 2015: 100 Jahre Shore A – Härteprüfung: Ein historischer Rückblick auf Entwicklung und Forschung zur Shore A – Messmethode mit Bezug

2.3.3 Sealing Material (Base Elastomer)

Most elastomer types rank in the mid-range of extrusion resistance. However, knowledge of the edges is important for seal design: seals made of silicone or fluorosilicone (e.g. VMQ, FVMQ) are particularly susceptible to extrusion. When designing, the recommended permissible gap width should be halved compared to other elastomers.

In general, all elastomers whose mechanical properties (tensile strength, elongation at break) decrease considerably at elevated temperatures are very susceptible to gap extrusion. Therefore, they often require support rings in order to provide a reliable sealing system.[16]

The decrease in strength at high temperatures is slightly lower for higher filled compounds than for less filled compounds.

Thermoplastic polyurethanes with relatively high hardness of 92 to 96 Shore A are known for their high wear resistance and strength. These properties make them highly extrusion-resistant sealing materials (see **Fig. 3**). "Polyurethane gaskets only require [plastic support rings] at very high operating pressures of 40 MPa and more at large gap widths."[17] This is why they are frequently found in hydraulics.

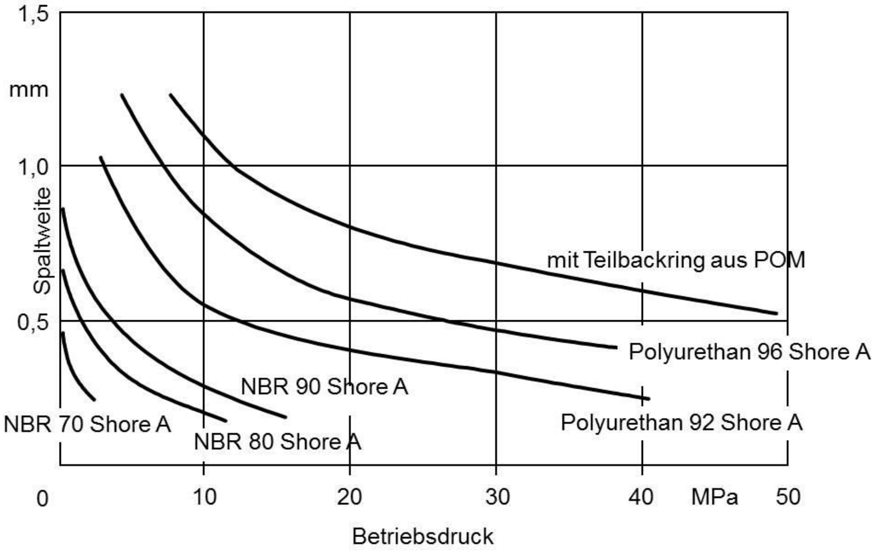

Fig. 3: Diagram of permissible gap widths as a function of operating pressure for various sealing materials and designs (support ring)[18] (Picture: Displayed with kind permission of VDMA Fluidtechnik)

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zur heutigen Prüpraxis, Dez. 2015, S.36, Onlineveröffentlichung: https://www.o-ring-prueflabor.de/files/fachwissen-100_-jahre_-shorea-12_2015.pdf

[16] Vgl. FLITNEY, R.: Seals and Sealing Handbook, Butterworth Heinemann / Elsevier, Oxford, ^{6}2014, S. 387

[17] translated from HOEPKE, E. et al.: Dichtungstechnik mit gummielastischen Dichtungen und Formteilen im Fahrzeug- und Maschinenbau, expert Verlag, Renningen-Malmsheim, 2000, S.148

[18] VDMA Arbeitskreis Fluiddichtungen: Dichtsysteme für fluidtechnische Anwendungen, CD-ROM, Datei: Lehrmaterial.ppt, 2005, Kapitel Schadensfälle, S. 8

2.3.4 Swelling or Chemical Degradation

An incompatibility of the fluid to be sealed with the sealing material can lead to unexpectedly high swelling. As a result, the seal is greatly softened, which reduces the resistance to gap extrusion. Swellings are uncritical between 5 and 10%. At higher swelling rates a sufficient safety against gap extrusion should be questioned, and if necessary, support rings should be used. Especially in the case of thermoplastic polyurethane seals, which are used at very high pressures, an inadmissible chemical effect (e.g. hydrolysis when using environmentally friendly hydraulic fluids) due to the hydraulic oil can also lead to greatly reduced strength properties and result in chipping at the sealing gap (see **Figs. 13 and 14**).

2.4 Temperature

Rubber materials behave viscoelastically, meaning their load limits are strongly temperature dependent. The risk of damage due to gap extrusion therefore increases with increasing temperature (see **Fig. 4**). In general, there is little data on the mechanical properties of elastomers at elevated temperatures. Determining load limits at elevated temperatures is very laborious. However, DMA analyzers are relatively well available today and are becoming more and more common. Although these do not allow any information on load limits, they can provide a complete database for FEA analyses via so-called multi-frequency analyses (which map the deformation resistance of the gasket material under the influence of temperature) together with the dynamically induced stiffening due to the speed of the deformation. If the degree of deformation of a seal under load is known, the risk of failure can be estimated. In case of doubt, hydraulic test rigs help to determine these limits experimentally.

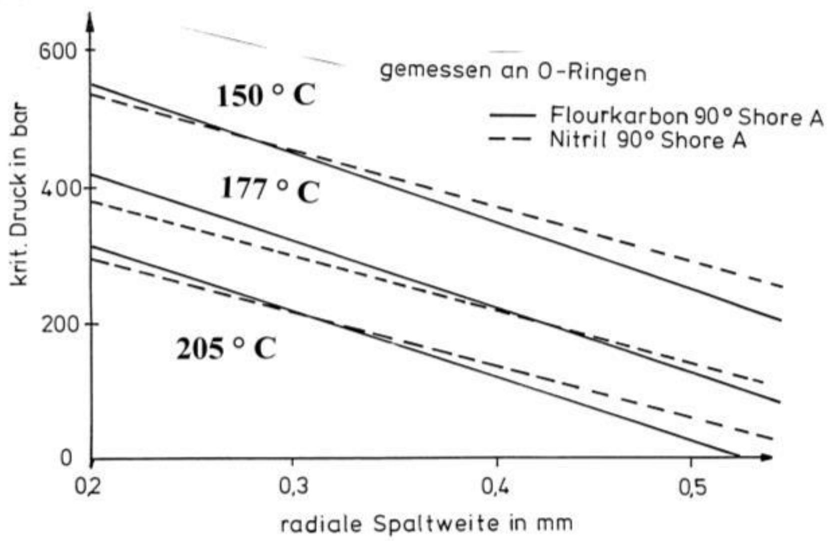

Fig. 4: The viscoelastic behavior of rubber materials increases the risk of gap migration at rising temperatures. (Fluorocarbon = FKM; Nitrile = NBR)[19]

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[19] RICHTER, Bernhard: Dichtungen sicherer machen in: KEM Konstruktion, Elemente, Methoden Technologische Informationen für Konstruktion und Praxis; 22, Heft 1, 1985, S. 78-80

3. Damage Pattern

3.1 Description of the Damage Pattern and Problematic Areas

The classic gap extrusion is one of the most impressive damage patterns of elastomer seals. The image of a cross-section of an almost completely unrolled O-ring is very memorable and clearly identifiable even by a layman (see **Figs. 5 and 9**). Such clear damage patterns are usually only caused by very sharp-edged groove recesses in combination with the corresponding gap and pressure. More typical and more frequent, however, is the damage pattern from **Fig. 6**.

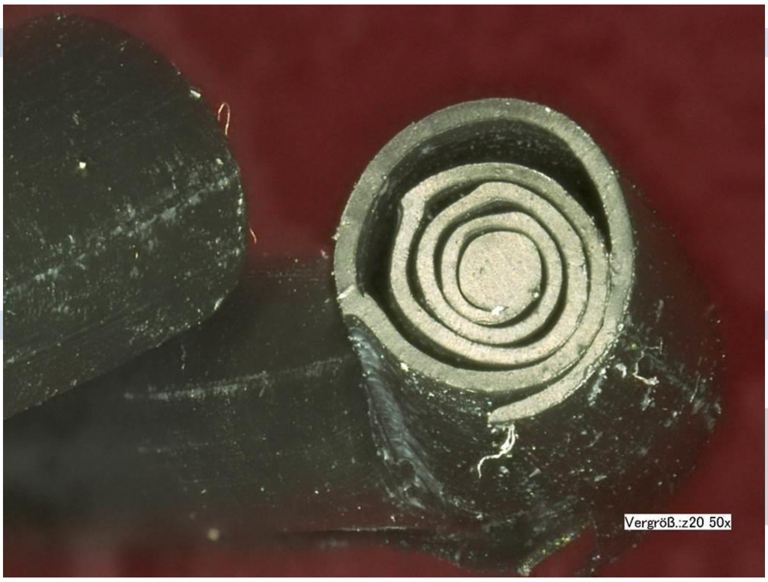

Fig. 5: Damage pattern of a gap extrusion, formed at 350 bar pressure and a gap of 0.05 mm, atypically and strongly formed as a result of a sharp-edged groove recess.

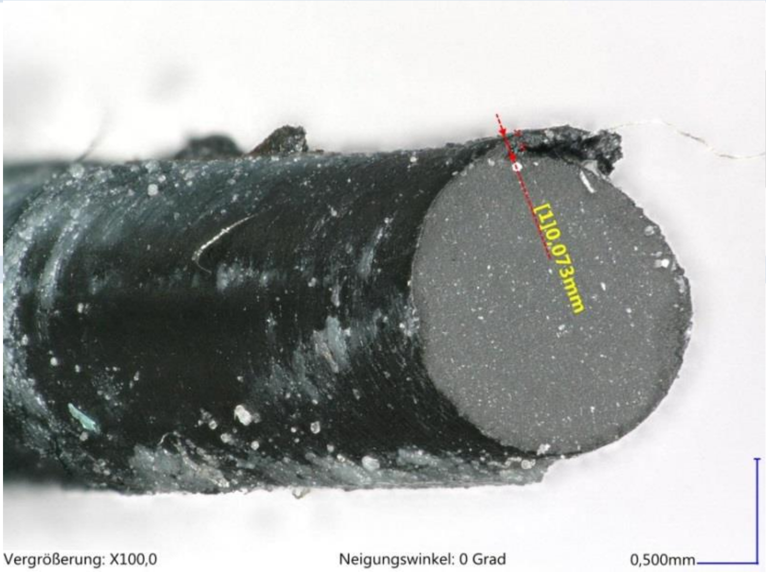

Fig. 6: Typical damage pattern of a gap extrusion

In general, peeling occurs during gap extrusion on the low-pressure side of the O-ring, usually only partially on the circumference, as a result of penetration into the sealing gap. The

separation of sealing material on the low-pressure side has at least the advantage that no detached rubber particles reach the medium side at the beginning of the damage.
"Often this damage pattern can only be found at one point of the circumference, which is the point with the greatest eccentricity and therefore the largest sealing gap." [20] (see **Fig. 8**). The remaining body of the seal is usually still fully rubber-elastic and, if measurable, the hardness has not changed significantly.

3.1.1 Damage Caused by Pressure Problems

Fig. 7: Damage to an O-ring at the grooved phase due to high pressure rise rates

3.1.2 Damage Caused by Constructional Problems

Fig. 8: O-ring after gap extrusion due to too large gap dimension: The area with the smallest remaining cord thickness (top of picture) represents the beginning of gap extrusion and is the point at the circumference with the largest gap dimension between piston and cylinder.

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[20] RICHTER, B.: Kap. 3.3.3 O-Ringe in: TIETZE, W.: Handbuch Dichtungspraxis, Vulkan-Verlag, Essen, ²2000, S. 249

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No.  Measure   Result
1    2 Points      0.22 mm
2    2 Points      0.23 mm
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Count: 0

Fig. 9: O-ring damaged by gap extrusion (NBR 70 ShA at a gap of 0.2 mm and a pressure of 200 bar) in cross-section: atypically and strongly formed due to a sharp groove edge

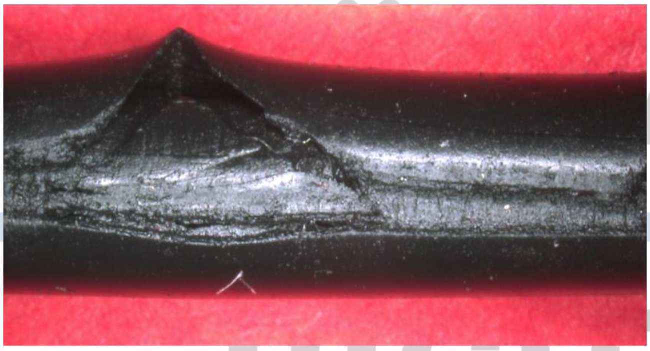

Fig. 10: Top view of an O-ring damaged by gap extrusion, section from Fig. 9

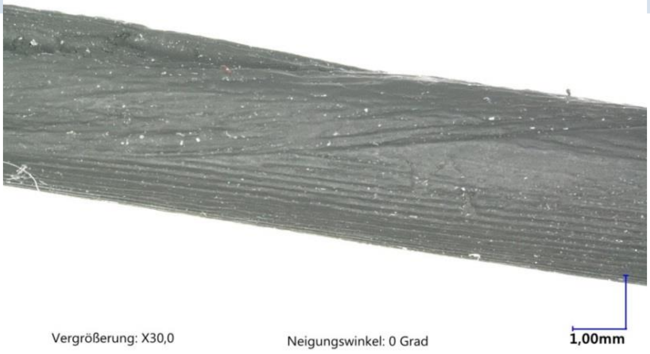

Fig. 11: Damage to an O-ring by a sharp-edged groove and dynamic pressure loads, this led to a twisting of the O-ring in itself

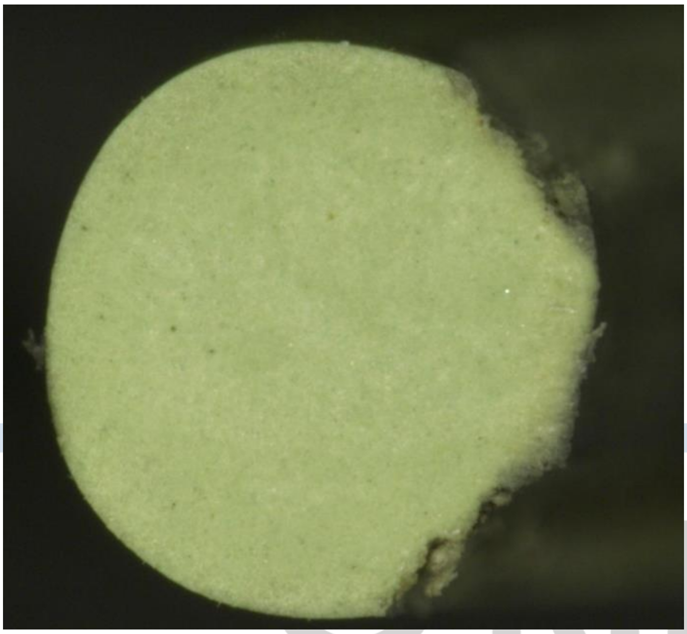

Fig. 12: Damage to a dynamically used O-ring at the groove edges due to high breakaway forces

3.1.3 Damages Caused by Problems with the Sealing Material

Fig. 13: Damage to a thermoplastic polyurethane seal at the sealing gap after strong chemical impact and resulting loss of strength.

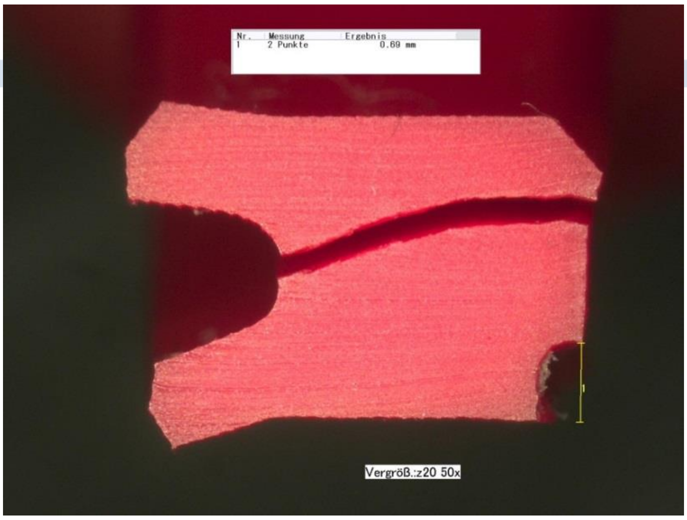

Fig. 14: Damage to the sealing gap of a hydraulic seal and resulting rupture due to hydrolysis

3.2 Effects of the Damage

This damage pattern does not develop abruptly, but over a longer period of time and then leads to failure of the seal as the damage pattern becomes more and more severe.
"Excessive abrasion wear and flow erosion occur as consequential damage in moving seals. After the sealing material has crumbled out due to extrusion, new material is pressed into the cavities created by the operating pressure, which also propagates in the seal. The resulting tensile forces are superimposed by friction forces and wear occurs. This in turn enables flow erosion."[21]

3.3 Differentiation from Similar Types of Damage

It is not always possible to clearly delimit the damage pattern of gap extrusion (= physical operational overload) from the damage pattern of the installation error (see **Figs. 15 and 16**: seal misalignment during installation and resulting squeezing). In case of doubt, the width of the peel-off must be checked with the theoretical maximum gap dimension of the installation space. The peelings caused by incorrect installation are usually much thicker than the maximum gap dimension. Damage caused by gap extrusion below 50 bar pressure is also unlikely.

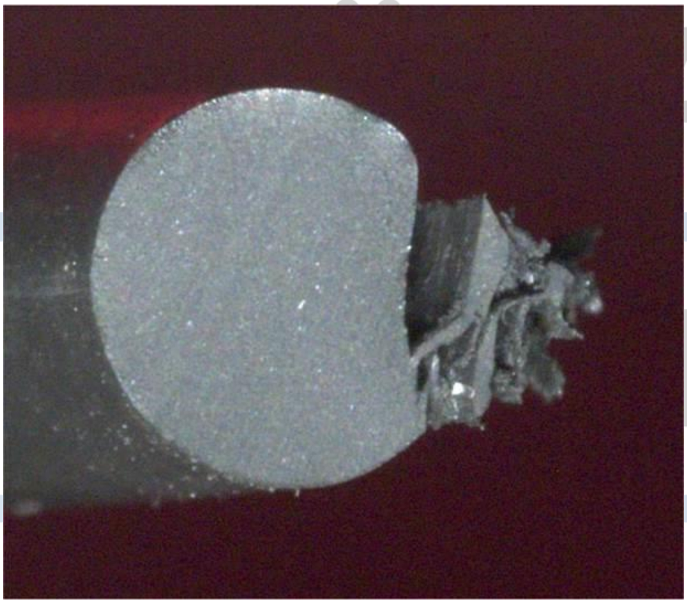

Fig. 15: Damage to an O-ring due to an assembly error

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[21] SCHRADER, Klaus: Hydaulik-Dichtungen Teil II: Schadensbilder, -ursachen, -vermeidung in o+p Ölhydaulik und Pneumatik, Heft 5, Band 26, 1982, S. 358 und 361

Fig. 16: Damage caused by a mounting error (compression)

The damage pattern of gap extrusion can also be confused with the damage caused by expanding air (see **Fig. 17**). However, in comparison to gap extrusion, this damage pattern always occurs on the pressure side and not on the low-pressure side.

Fig. 17: Damage pattern air in hydraulic oil, the damage is found on the pressure side in contrast to gap extrusion.

In the case of the damage of a groove overfill (see **Fig. 18**), which looks similar to a gap extrusion, material is also located outside the cross-section. In the case of groove overfilling, however, material drives on both sides are characteristic.

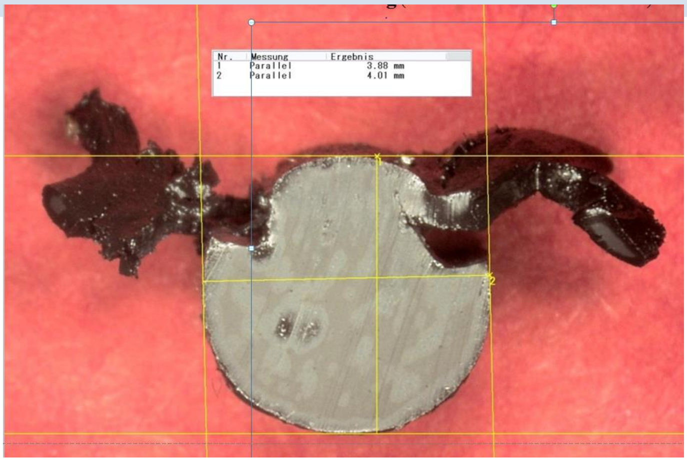

Fig. 18: Cross-section of an O-ring destroyed by groove overfilling: the incompressibility of rubb-er materials results in very high reaction forces, typical for this damage are the material drives on both sides.

4. Preventative Measures

The most important prerequisite for damage prevention is an understanding of this damage mechanism and its causes. The damage pattern of gap extrusion is primarily a gasket design problem, which is why it cannot be emphasized often enough that the training of designers with elastomer expertise is highly recommended.

If there is the possibility of selecting from different sealing materials with comparable material properties, the compound with greater hardness, higher modulus and higher strength should be preferred.

In special cases, multi-component gaskets are used which either consist of an elastomer/textile mix or in which only critical areas are reinforced with textile to make them more resistant to gap intrusion.[22]

If the rubber material side is already fully exhausted, only design changes remain. By using extrusion-resistant support rings, this damage pattern can be prevented in static applications, but also in slow translational or rotating movements. Support rings usually have a rectangular cross-section and are available on the market as closed or split rings and are mounted on the low-pressure side of the seal. They are usually made of a thermoplastic material, glass fiber reinforced PTFE (Teflon®) or hard elastomers. PTFE is characterized by its good sliding properties and its almost universal chemical and high thermal resistance. Today, biaxial, stabilized PTFE, is mostly used, which has been mechanically treated in such a way that it is less susceptible to creep, relaxation and extrusion.[23] Support rings can easily be manufactured with high precision, so that the critical gap can be reliably covered. "At low and medium pressures, the good sliding properties of PTFE allow coarser machining tolerances and roughness depths, since the worn PTFE particles of the support ring practically compensate the surface roughness and leave a lubricating film on the metal surface."[24]

By using filled PTFE support rings which do not tend to cold flow, high pressures can be reliably sealed: "...with stationary machine parts 400 bar pressure and gap widths up to 0.3 mm, (...) the same applies to axially moving parts and pressures up to 250 bar."[25]

In some cases, the seal position can be relocated so that the seal is less exposed to temperature. Where possible, static axial seals are preferable to radial ones, as axial seals do not have an extrusion gap or can be severely limited. Furthermore, reducing the edge radii to 0.1 - 0.05 mm can prevent a gap extrusion.

5. Practical Tips (Testing Possibilities / Standard Recommendations)

Since this damage pattern is triggered by a combination of several causes and often only occurs after a high number of stress cycles, it is difficult to make an estimate in advance. It is

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[22] KOHLER GmbH: Hydraulikdichtungen, Dezember 2013, S.9, Onlineveröffentlichung: https://www.kohler.de/service/Prospekte/Hydraulik-Dichtungen.pdf (Webseite aufgerufen am 15.03.2019)

[23] FLITNEY, R.: Seals and Sealing Handbook, Butterworth Heinemann / Elsevier, Oxford, ^{6}2014, S. 81

[24] PESCHK, G.: O-Ringe oder Rundschnurdichtringe in: SCHMITT, Wilhelm: Kunststoffe und Elastomere in der Dichtungstechnik, Verlag W. Kohlhammer, Stuttgart, 1987, S. 237

[25] Ebd., S. 237f.

therefore advisable to test seals on test rigs that are as realistic as possible and to carry out a thorough analysis of returns from field tests. A very pragmatic approach is to use thermoplastic polyurethane O-rings, molded sealing rings or piston and rod sealing elements as far as possible in critical applications. This also has the advantage that they can also be machined and are therefore available at short notice.

ISO 3601-4[26] provides the designer with helpful information on the design of support rings but does not specify when these should be used.

Of course, nowadays there is also the possibility of predicting the gap extrusion with FEM systems. However, the significance depends strongly on the suitable material models and assumptions regarding the actual seal friction. Practical experiments will presumably not be completely replaceable by numerical simulation in new applications in the foreseeable future.

6. Other

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[26] ISO 3601-4: 2008-06 Fluid power systems- O-rings- Part 4: Anti-extrusion rings (back-up rings)