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Improved Urethane Materials for Fluid Power Composite Seals (ISGATEC Conference)

English translation
of the presentation at the
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Improved Urethane Materials for Fluid Power Composite Seals

Th. Schwarz

1. Introduction

Combined sealing assemblies consisting of a sealing ring made of PTFE and an elastomeric O-ring are widely used in a wide variety of equipment such as presses, injection moulding machines, machine tools e.g. milling machines, in equipment for the food and pharmaceutical industry such as filling, metering and mixing units as well as in mobile hydraulics e.g. excavators and forest machinery.

There are several different names for this kind of sealing element: sliding seals, step seals or even composite seals [1]. All the seals that are available on the market, whether they are co-axial (usually used as piston seals) or in-line (shaped lip with higher preload for the use as rod seals), consist of a more or less hard sliding element based on PTFE or a PTFE-compound (filled with bronze, glass, molybdenum disulfide, graphite or carbon fibres) and an elastic preload element such as O-rings or square section rings based on nitrile or fluororubber in a hardness range from 70 to 90 Shore A. Sometimes, the sliding rings are made from plastics e.g. UHMWPE, polyamide or polyurethanes. Typical types of these seals are shown in Figure 1 and 2.

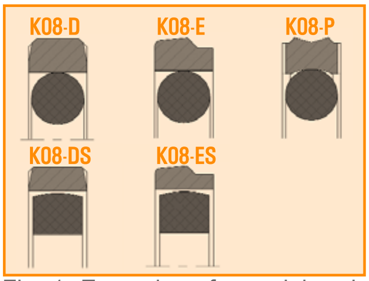

Fig. 1: Examples of co-axial and in-line composite seals for piston sealing

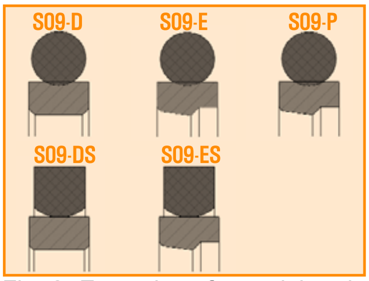

Fig. 2: Examples of co-axial and in-line composite seals for rod sealing

1.1. Requirements for Composite seals

Composite seals are often used in systems that are working at very low speed and high control accuracy. Therefore this kind of seal must meet the following range of requirements:

• Low friction and no occurence of stick-slip
• Low leaking rates
• Long lifetime, which means high wear resistance
• Resistance against pressure and extrusion
• Easy to install

Normally composite seals based on a sliding element made of PTFE or a PTFE compound meet the following requirements:

• Due to the outstanding friction behaviour of PTFE-based materials, low friction and the avoidance of stick-slip can be guaranteed for these seals if a suitable lubricant is used in the system.
• Most compounds show acceptable pressure and extrusion resistance; problems can occur if unsuitable compounds are used or operated with too large an extrusion gap.

Looking to the remaining requirements, some weak points of these seal combinations become visible.

• Normally composite seals in particular if used as rod seals, show relatively high rates of leakage. To improve the sealing performance it is necessary to mount these seals in a tandem configuration [1, 2, 3], that means to combine either two composite seals or one composite seal with an U-ring or lip seal made of polyurethane or an elastomer.
• In general the wear resistance of PTFE materials, compared to many other polymers, is mediocre to moderate [4, 5], and therefore an acceptable lifetime can only be attained if a fully developed lubrication film exists. Furthermore the poor wear properties and especially the notch sensibility of PTFE can cause damage during the fitting process and lead to unacceptable leakage and breakdown of the seal through leakage wear. Small defects or damage to the seal by a scored, scratched or indented rod can lead to the same result.
• Due to the limited elasticity and therefore high residual deformation of PTFE materials, fitting and subsequent calibration of the seals must be done very carefully.

2. Test Results

2.1. Materials

The tests were performed with following materials

• ECOPUR®: Thermoplastic polyurethane elastomer (TPU) based on polyester with a hardness of 48 Shore D, especially developed for U-cups or lip seals for mineral oil hydraulics; (Manufacturer: ECONOMOS® Austria GmbH)

• X-ECOPUR®-57D: Thermoplastic polyurethane based on polyester with a hardness of 57 Shore D for use as composite seals in mineral oil hydraulics; (Manufacturer: ECONOMOS® Austria GmbH)

• XH-ECOPUR®-60D: Thermoplastic polyurethane elastomer with a hardness of 60 Shore D with an outstanding chemical and hydrolysis resistance for applications in mineral oil, biodegradable hydraulic fluids (HETG and HEES, etc.) and water-based fluids (HFA, HFB); (Manufacturer: ECONOMOS® Austria GmbH)

• Various PTFE-Compounds
  - Virgin PTFE
  - PTFE filled with 15% glass and 5% molybdenum disulfide (PTFE 15% Glass / 5% MoS_2)
  - PTFE filled with 40% Bronze (PTFE 40% BZ)
  - Friction-modified PTFE (virgin PTFE modified with a friction-reducing additive package)

• HYTREL: Ether-ester block copolymer with a hardness of 63 Shore D

2.2. Mechanical Investigations

The test results discussed in this paper are only dealing with the mechanical properties that influence seal installation and assembly and their effects on extrusion. These are mainly the hardness, the modulus at strain, the tensile strength and the residual deformation. On one hand the residual deformation (tensile set) is measured out of the hysteresis curve from the uniaxial tensile test, on the other hand it is a result from the fitting of a rectangular ring over a mandrel with a deformation of 20%. The residual deformation is determined after one hour (analogous ?) the compression set (=tensile set).

2.3. Test Rig Investigations

The tests were performed with a composite rod seal S09-E based on various sliding materials preloaded with an NBR O-ring of 70 Shore A (Fig. 3).

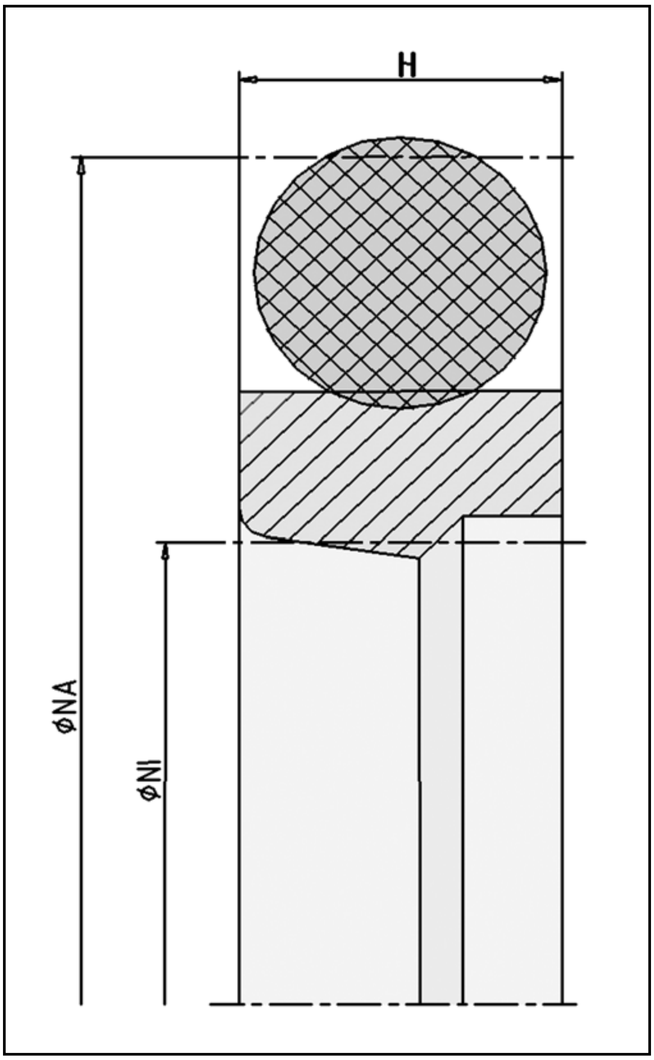

Fig. 3: Cross-section of the test seal S09-E

The schematic drawing of the test cell is shown in Fig. 4, the tests were performed in a pulling/pushing operating mode over running metres of 40 km at a temperature of 100°C and a test pressure of 400 bar. All test parameters are shown in Table 1.

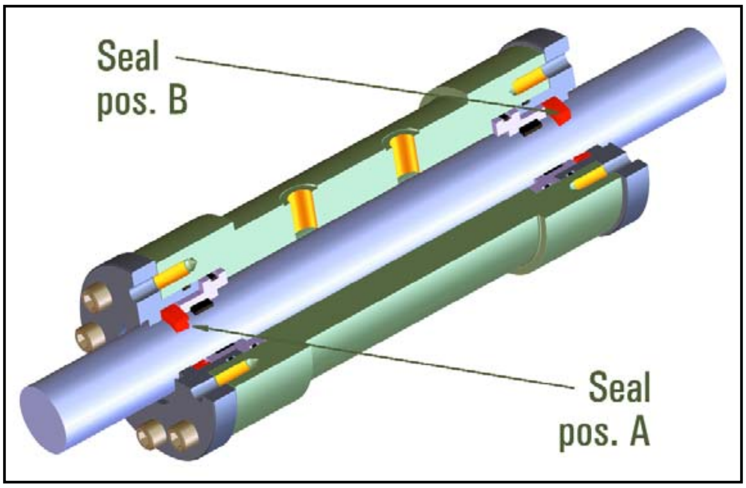

Fig. 4: Schematic drawing of the test cell

Seal Type	S09-E, machined
Housing [mm]	50x65x6,3
Test pressure [bar]	400
Test temperature [°C]	100
Sliding speed [m/s]	0,5
Operating mode	pulling/pushing
Running metres [km]	40
Medium	HLP 68
Extrusion gap [mm]	0,15
Rod material	V 945, hard chromed
Rod surface	Ra= 0,2 µm

Table 1: Test conditions of test rig investigations

The seals were rated according to their friction behaviour as a function of the running metres, the leakage, wear and extrusion characteristics.

The investigations of the stick-slip characteristics were performed on a test rig with a stationary test cell and a special hydraulic drive unit for the rod. Therefore only a small mass has to be moved, this allows a good investigation of stick-slip phenomena (Fig. 5).

The stick-slip status was estimated by measuring the changes of the velocity of the piston rod due to changing coefficients of friction (stick-slip). The velocity of the rod was determined with a piezoelectric acceleration transducer. For this investigation composite seals, type S09-E, dimension 45x55x4, at a temperature of 60°C and a pressure of 200 bar have been used. The speed ranged from 0,1 to 0,005 m/s.

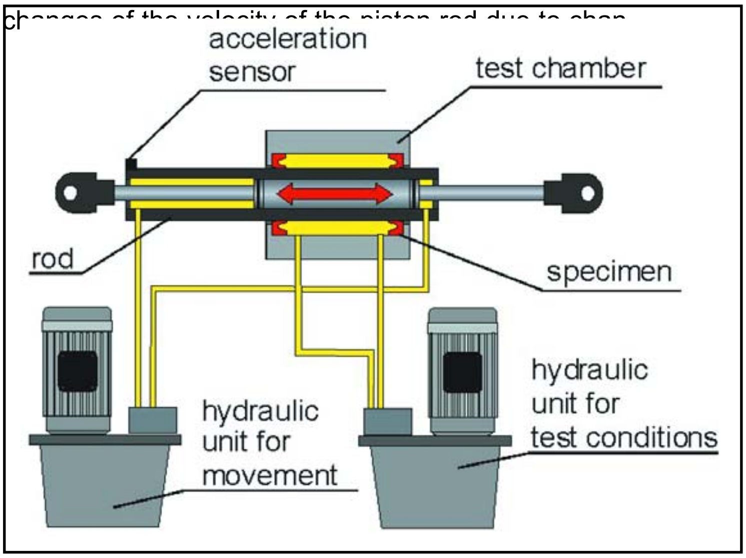

Fig. 5: Scheme of the test rig for stick-slip investigations

3. Results and Discussion

3.1. Mechanical Investigations

Fig. 6 shows the stress-strain graphs for the polyurethane elastomers ECOPUR® and X-ECOPUR®-57D and the virgin and Bronze-filled PTFE grades. The hard polyurethane grade has an approximately 2 times higher modulus than the standard U-cup grade.
The PTFE grades that have approximately the same hardness as X-ECOPUR®-57D (see. Fig. 7), show a significantly higher 10%-modulus than the polyurethane grade. This is a 35% increase over the virgin and approximately 70% for the bronze grade, that means the PTFE seals need higher forces during the installation procedure, especially in the case of piston seals.
Looking to the complete stress-strain graphs we can also see that the polyurethanes show superior tensile strength compared to the PTFE grades (Fig. 8), which should result in a higher extrusion resistance of the seals.

Mechanical

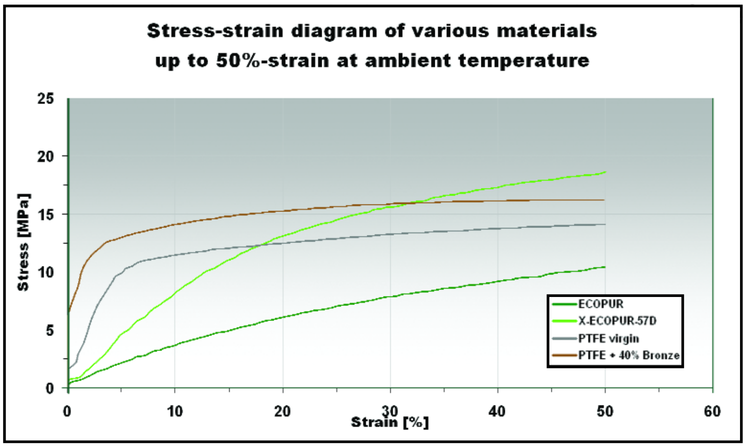

Fig. 6: Stress-strain graphs of various sealing materials

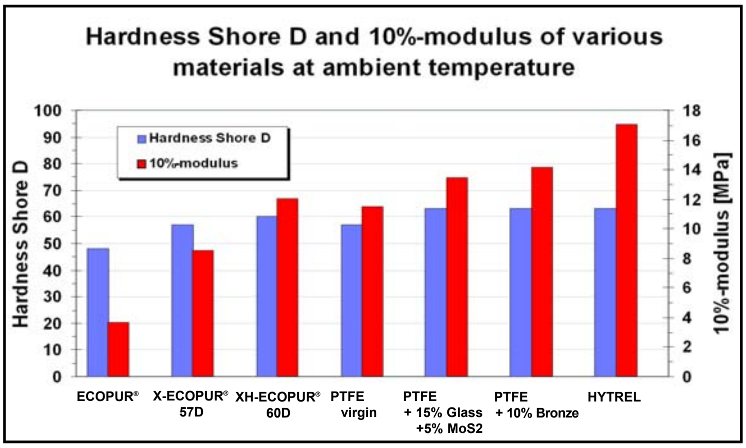

Fig. 7: Hardness and 10%-modulus of sealing materials

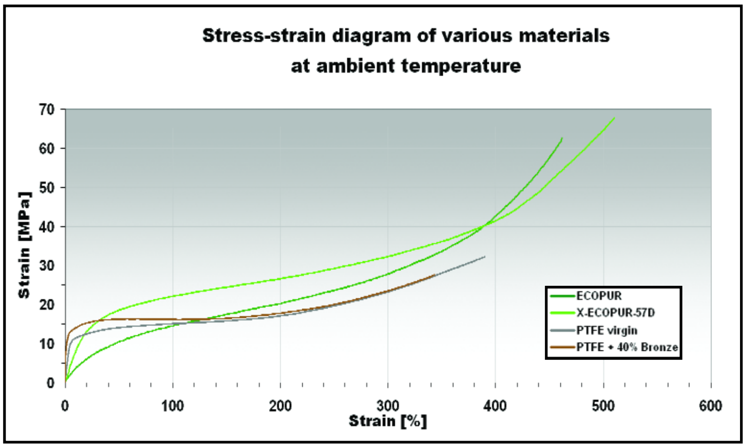

Fig. 8: Stress-strain graphs of sealing materials

The hysteresis curves (Fig. 9) demonstrate the difference in the deformation characteristics of virgin PTFE compared to the polyurethane grade ECOPUR®. Virgin PTFE shows the typical plastic deformation behaviour of a soft thermoplastic with high hysteresis loss and high residual deformation whereas the polyurethane shows an elastic tensile curve with a small hysteresis loss and residual deformation.

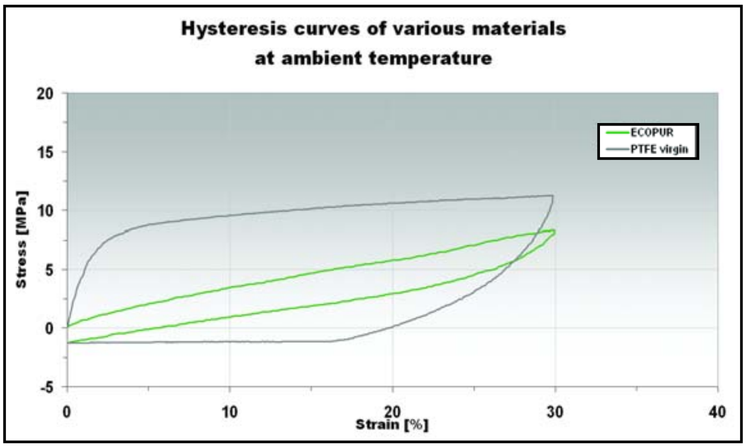

Fig. 9: Hysteresis curves of virgin PTFE and ECOPUR®

The superior tensile set of the polyurethane grades is also clearly demonstrated by Fig. 10. The polyetherester elastomer shows a 3 times higher tensile set as X-ECOPUR®-57D and the PTFE grades have more than 10 times higher values. This result is of major importance for the fitting of piston seals, because due to the small tensile set of the polyurethane a following calibration procedure of the composite seals is usually not necessary.

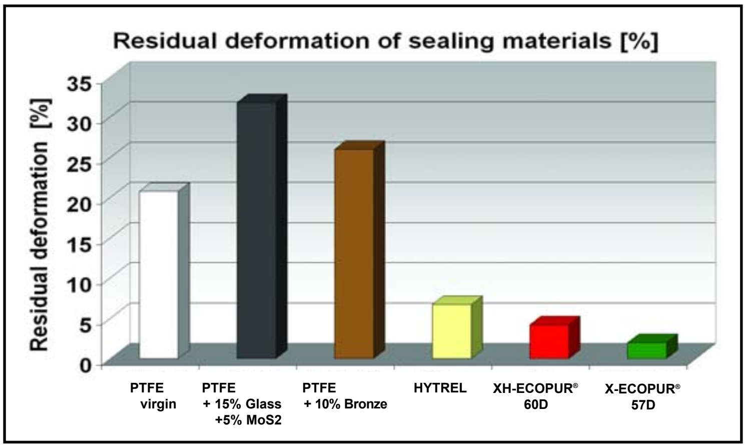

Fig. 10: Tensile set of various sealing materials

The following conclusions of the mechanical investigations can be verified:

• Although hardness of the polyurethanes is in the same range as that of the corresponding PTFE compounds, the polyurethanes show smaller modulus and therefore better installation properties.

• Furthermore the polyurethanes show a superior elasticity, which results in a distinctly smaller tensile set, which makes the fitting as well as the calibration process of the seals easier.

• Nevertheless the polyurethanes have a lower modulus and a softer deformation curve, the tensile strength is clearly higher which should result in a better extrusion resistance of the seals.

The chemical resistance of these kinds of materials will not be discussed in this paper; many papers exist [6-9] proving, that special polyurethane elastomers have a sufficient chemical resistance in mineral oils or, like H-ECOPUR® based urethanes, also in water-based or biodegradable power fluids.

3.2. Seal Investigations

Fig. 11 shows the frictional forces of various seal types as a function of the running metres. Astonishingly, the polyurethane grades, X-ECOPUR®-57D and XH-ECOPUR®-60D, show a frictional force of approximately 550 N, which is smaller than most of the PTFE compounds. The highest friction measured is for the glass/MoS2 compound this should be due to the glass fibre loading. Furthermore, it should be considered that the friction of the polyurethanes slightly decreased during the first 2000 m and afterwards it is more or less constant for the whole period of 40 km, whereas most of the PTFE grades show a decreasing friction over the whole period. This should be the result of wear of the PTFE rings on the one hand and coating of the rod with a PTFE layer with increased test duration and wear on the other.

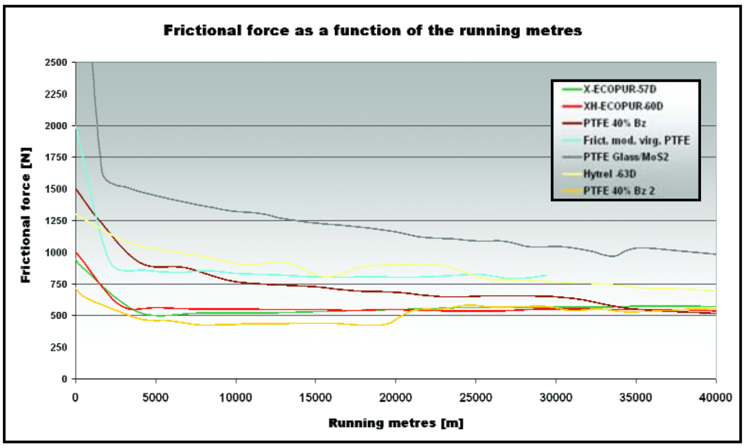

Fig. 11: Frictional force of various composite seals as a function of the running metres.

The leakage behaviour of these seals is shown in Fig. 12. Compared to the PTFE seals the polyurethanes have a superior tightness which is demonstrated in leakage values that are a magnitude smaller, although the seals have a comparable friction force. Of particular interest are the results of the two PTFE-Bronze grades that have been tested: the grade PTFE Bz. 2, based on a 40% Bronze filled PTFE, shows nearly 5 times higher leakage than the other bronze grade and therefore lower friction values according the hydrodynamic lubrication.

All the more important is the sealing behaviour of the polyurethanes, this is of major interest because these seals exhibit low friction combined with very low leakage, which is unusual for composite seals.

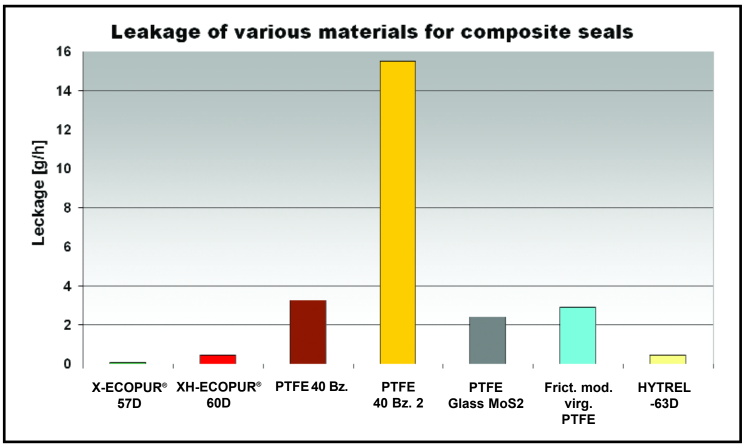

Fig. 12: Leakage of composite seals

As expected the urethanes have a better extrusion resistance than the PTFE compounds and the Hytrel grade (Fig. 13). The length of the extruded parts of most of the PTFE grades is nearly 30 times higher and also the Hytrel grade shows 5 times larger extrusion. Fig. 14 shows photos of the extrusion and wear characteristics of 3 PTFE Bronze grades and the polyurethane grade X-ECOPUR®-57D. These photos demonstrate the totally different wear and extrusion resistance of PTFE compounds of the same composition but of different suppliers. Nevertheless not one of the PTFE compounds has comparable wear and extrusion resistance as the polyurethane grade.

Looking to the sliding zones after the full test length of 40 km, the outstanding wear properties of the polyurethane elastomer X-ECOPUR®-57D can be seen very clearly (Fig. 15). The polyurethane shows little to no wear and the turning grooves from the manufacturing process are still visible, whereas at the "good" bronze compound all the turning grooves are worn. At the "poor" bronze compound strong abrasion and leakage wear can already be detected.

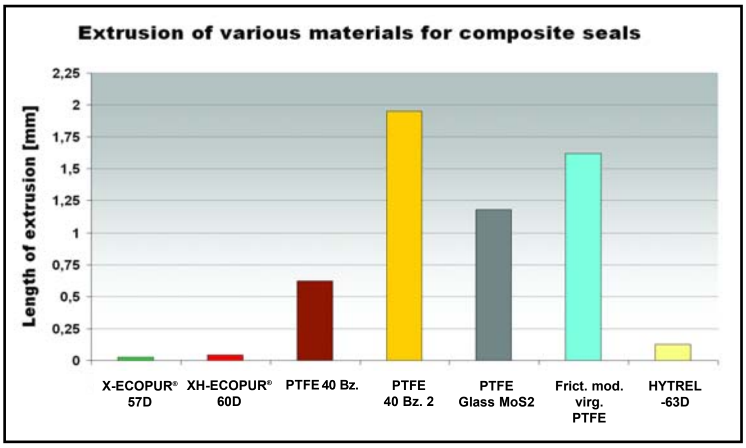

Fig. 13: Gap extrusion of composite seals

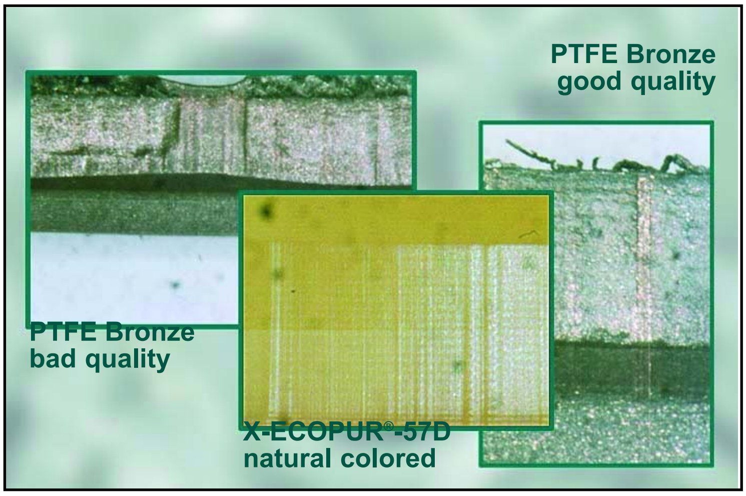

Fig. 15: Microscopic investigations of the sliding surface of composite seals

Fig. 14: Gap extrusion and wear of composite seals

Figures 16 to 18 compare the sealing properties of X-ECOPUR®-57D to various commercially available composite seals based on different PTFE compounds. In principle the results are corresponding to those we discussed earlier. The polyurethane elastomer shows superior leakage, extrusion and wear characteristics and competitive friction properties.

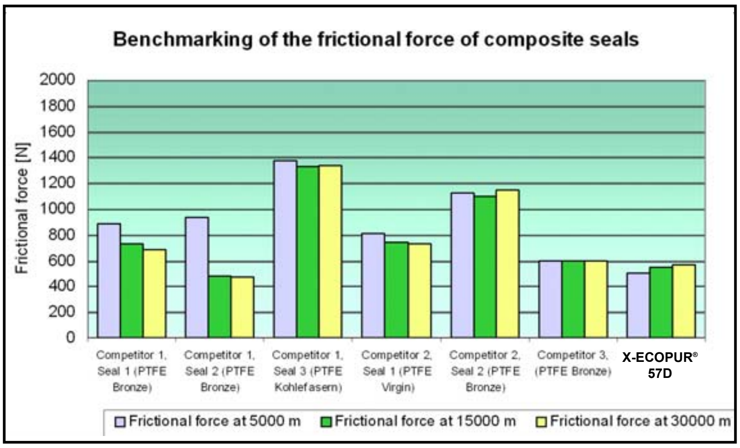

Fig. 16: Friction properties of commercially available composite seals compared to X-ECOPUR®-57D

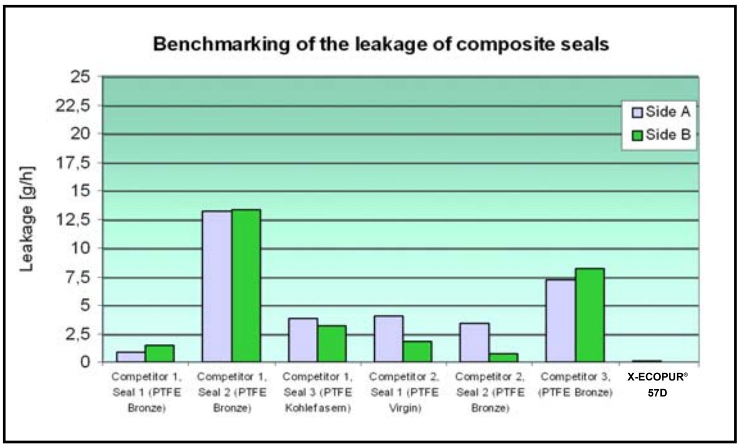

Fig. 17: Leakage characteristics of commercially available composite seals compared to X-ECOPUR®-57D

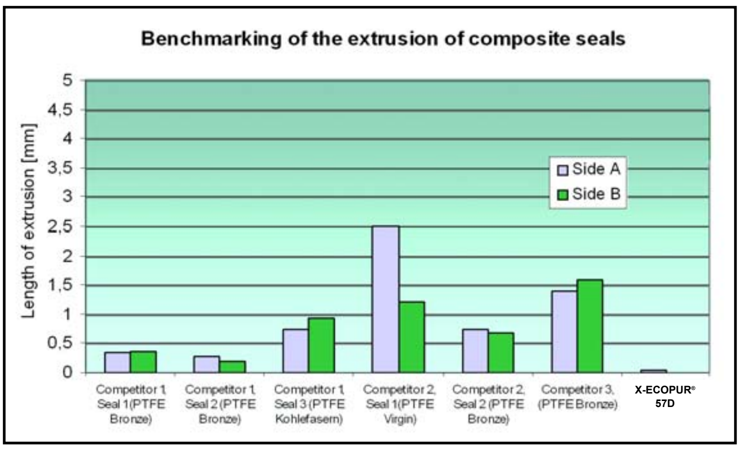

Fig. 18: Extrusion characteristics of commercially available composite seals compared to X-ECOPUR®-57D

Finally a short summary concerning the stick-slip behaviour of the seals tested. It is of vital importance that composite seals should have comparable friction properties, both at medium hydraulic speeds and especially at very slow velocities that normally occur in, for example, machine tools etc.

Fig. 19 shows the acceleration of the piston rod as a function of time for a composite seal based on a PTFE-bronze (40%) compound and X-ECOPUR®-57D. The top graphs show the acceleration traces at a rod speed of 0,066 m/s and it can be clearly seen that the rod is moving with a constant speed apart from some vibrations of the whole system. The bottom traces describe the situation for a reduced rod speed of 0,043 m/s. It is obvious that the rod does not move under a constant speed, but steadily changes between acceleration and braking, therefore it is working in a typical stick-slip mode. So this investigation proves that stick-slip occurs for both seal types at the same rod speed, which would not be expected from previously held knowledge.

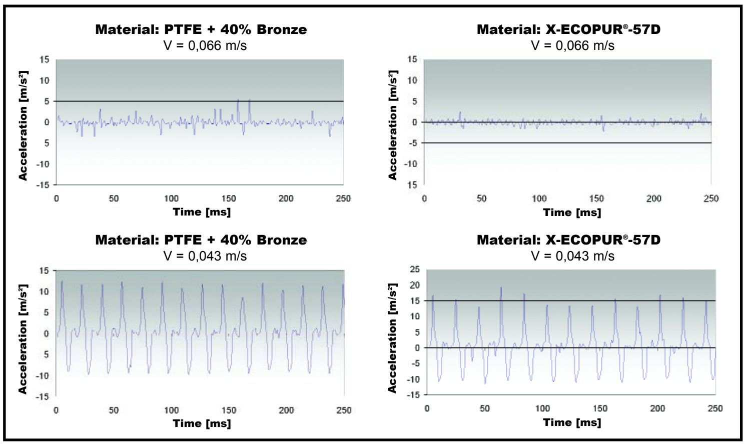

Fig. 19: Investigation of the stick-slip characteristics of composite seals

Conclusio

4. Conclusions and outlook

The investigations discussed in this paper prove that composite seals based on special polyurethane elastomers are meeting all the necessary requirements:

- Low friction and no stick-slip behaviour
- Outstanding leakage behaviour
- Superior extrusion and wear characteristics
- Good installation and assembly properties.

Due to this performance, seals based on these special polyurethanes are an ideal replacement for commercial PTFE based composite seals, provided that the seals are compatible with the working fluid and the temperatures do not exceed the maximum working temperatures of these materials. therefore these sealing elements can be successfully installed in injection moulding units, machine tools as well as in mobile hydraulics and in metering and mixing units.

At ECONOMOS® soft and elastic materials can also be machined into seals which are commonly manufactured from PTFE. Therefore these kinds of seals are also available in single units as well as short runs on a just in time basis. Furthermore due to the thermoplastic structure of the material any seal profile can also be produced in high quantities by injection moulding thereby providing significant cost savings.
In summary; seals and sealing elements manufactured from the materials described are suitable for higher pressures or larger gaps than PTFE seals and have an outstanding wear resistance leading to longer lifetimes. These benefits along with the installation, assembly, low speed operation and sealability advantages ensures that fluid power sealing has entered the 21st century.

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ECONOMOS® Austria Gesellschaft m.b.H.
Gabelhoferstrasse 25
A-8750 Judenburg
Phone: +43 3572 82555-0
fax: +43 3572 82555-58

Email: judenburg@economos.com
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HEADQUARTERS
Economos Austria GmbH.
Gabelhoferstr. 25
A-8750 Judenburg
Phone: +43 3572 82555
Fax: +43 3572 82555-58
E-mail: judenburg@economos.com
Internet: http://www.economos.com

Sales Eastern Europe & Ex-SU
Economos Austria GmbH.
Iz NÖ Süd, Str. 1, Obj. 50
A-2351 Wr. Neudorf
Phone: +43 2236 62207
Fax: +43 2236 62207-7
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AUSTRIA
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Fax: +43 3843 51155
E-mail: st.michael@economos.com
Internet: http://www.economos.at

AUSTRALIA
Economos Australia Pty. Ltd.
2/107 Beaconsfield Street
Silverwater NSW 2128
Phone: +61 2 9748 7466
Fax: +61 2 9748 7006
E-mail: australia@economos.com
Internet: http://www.economos.com

ARGENTINA
Seal Jet Economos S.A.
Tucumán 4140
(3000) Santa Fe, Argentina
Phone: +54 342 455 3644
Fax: +54 342 453 0299
E-mail: sealjet.argentina@economos.com
Internet: http://www.economos.com

BELGIUM
Economos Belgium N.V.
Industriezone 5 Mollem 36
B-1730 Asse
Phone: +32 24 523600
Fax: +32 24 523518
E-mail: belgium@economos.com
Internet: http://www.economos.be

CANADA
Economos Canada Inc.
5777 Coopers Avenue
Mississauga, Ontario L4Z 1R9
Phone: +1 905 712 1600
Fax: +1 905 712 1606
E-mail: canada.sales@economos.com
Internet: http://www.economos.ca

CHINA
Economos (Qingdao) Seal Tech Co. Ltd
Southern side of Zhuzhou Road,
266101Qingdao, China
Phone: +86 532 88702609 / 88701660
Fax: +86 532 88702325
E-mail: china.sales@economos.com
Internet: http://www.economos.cn

CZECH REPUBLIC
Economos Riha CZ, s.r.o.
Cernokostelecká 128/161
102 00 Praha 10
Phone: +420 267 900 711
Fax: +420 267 900 741
E-mail: praha@economos.cz
Internet: http://www.economos.cz

FRANCE
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Parc d´activités des Arpents
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Fax: +33 1 60 348537
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GERMANY
Economos Deutschland GmbH.
Robert-Bosch-Strasse 11
D-74321 Bietigheim-Bissingen
Phone: +49 7142 5930
Fax: +49 7142 593110
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Economos Italia S.r.l
Via E. Fermi 42
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Fax: +39 045 8648623
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Internet: http://www.economos.it

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Economos India Private Ltd.
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Fax: +91 11 26932612
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JAPAN
Economos Japan K.K.
MT No. 2 Build. 4-19-2,
Shimomaruko, Ohta-ku
Tokyo 146-0092, Japan
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Fax: +81 3 5732 3303
E-mail: tokyo@economos.com
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MALAYSIA
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No 12, Jalan PJS 7/21,
Bandar Sunway, Petaling Jaya,
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NETHERLANDS
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Economos Philippines Co. Ltd.
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E-08191 Rubi (Barcelona)
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SWEDEN
Economos Sverige AB
Hammarby fabriksväg 29 - 31
120 33 Stockholm, Sweden
Phone: +46 84 620180
Fax: +46 84 620140
E-mail: sweden@economos.com
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SWITZERLAND
Economos Schweiz GmbH
Hungerbüelstrasse 17
CH-8500 Frauenfeld
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THAILAND
Econosto (Thailand) Limited
99/28-31 Soi Wat Ladprao,
Ladprao Road, Ladprao
Bangkok 10230, Thailand
Phone: +66 (0)2 9316868 / 79
Fax: +66 (0) 2 9316880 / 1
E-mail: econthai@econostothai.com
Internet: http://www.econostothai.com

UKRAINE
Economos-Ukraine
Ul. O. Teligi, 15A
04112 Kiev , Ukraine
Phone: +380 444401181
Fax: +380 444407556
E-mail: economos@svitonline.com
Internet: http://www.economos.com.ua

UNITED KINGDOM
Economos UK Ltd.
83 Buckingham Avenue
Slough, Berkshire
SL1 4PN
Phone: +44 1753 696565
Fax: +44 1753 696192
E-mail: uk.sales@economos.com
Internet: http://www.economos.co.uk

USA
Economos USA Inc.
26820 Fargo Avenue
Cleveland, OH 44146
Phone: +1 216 3782600
Fax: +1 216 3782606
E-mail: usa@economos.com
Internet: http://www.economosusa.com