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Tribological investigation of friction coefficient in pneumatic seals with a special pin-on-disc setup

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Abstract. This article presents an experimental method for measuring friction in seals for pneumatic actuators using a pin-on-disk tribometer in a linear reciprocating sliding motion. A special device was designed to test a segment of seal cut out of a seal ring to replicate the working conditions of the piston seals. Friction tests were carried out with spring-energised seals made of graphite-filled PTFE. The counterpart for the friction test was a portion of an actual cylinder barrel of a pneumatic actuator. The coefficient of friction was measured under different loads to replicate several mounting preloads. Moreover, the experimental results were compared to the friction coefficient measured with a flat pin of the same seal material against a flat counterpart. The comparison between the two test setups allowed the authors to study the effect of the contact geometry and the applied load on the tribological performance of the seal. These preliminary measurements of stiffness and coefficient of friction are the basis for further investigations and measurements of elastic, viscoelastic and friction properties at the lip-barrel contact to develop a wear-damage model of lip seals.

1. Introduction

Pneumatic actuators can be successfully used in automatic mechanical devices provided that in-depth knowledge of the operating conditions of these components. As a result, defining and measuring the performance of pneumatic actuators in terms of friction force and durability has become essential. The sliding components in the actuators (gaskets, bushings and guide rings) have a decisive influence on performance and durability. In particular, the choice of the sealing type (lip, rounded lip, lobed, etc.), geometry and material, seat configuration, machining tolerances, lubrication conditions, and surface finish is of strategic importance to ensure the optimal sealing capacity, low friction, and high wear resistance. Frictional analysis in pneumatics involves experimental or numerical/analytical studies on complete actuators or seals considered individually. In the first type of approach, on complete actuators, the objective is usually to optimise the system performance and/or the mating materials considering the physical and mechanical parameters of influence. In the second type of approach, with single seals, the objective is generally to predict the mechanical and friction behavior at the contact site to optimise the sealing element geometry.

Several experimental methods to determine the friction force in double-acting cylinders at a constant speed as a function of the pressure differential through the piston have been developed by Belforte et al. [1], [2], Schroeder and Singh [3] and Kazama and Fujiwara [4]. Particularly effective was measuring the friction force in actuators by a stationary force sensor rather than by a moving one fixed to the rod.

This solution makes the measurement insensitive to dynamic loads [2]. Belforte et al. [5] [6] also demonstrated an influence on the measurement of rod movement direction (inward and outward stroke), and a procedure was outlined to separate the individual friction contributions of gaskets. Wassink et al. [7] presented a model to estimate the coefficient of friction in lip gaskets subjected to alternating motion considering the physical characteristics of the rubbing surfaces, the viscous losses due to the lubricant and the hysteresis phenomena of the material. These are aspects of great importance in the presence of elastomer or plastomer seals. Salant et al. [8] presented a multi-scale numerical model for sliding seals combining the structural FEM analysis of deformations, the contact mechanics simulation with a rough surface and the fluid mechanics within the lubricating film. The model allowed the authors to analyse the seal performance in multiple operating conditions. Pinedo et al. [9] developed a three-dimensional model to consider the effect of incorrect seal assembly resulting from the eccentricity of the contact between the seal and rod. The results, which closely matched the experimental data, showed that a minor eccentricity of the rod could lead to significant changes in the contact force and, therefore, in the deterioration of the gasket itself.

In general, therefore, friction measurements in pneumatic applications require the preparation, not always easy, of test benches to reproduce the actual operating conditions of the cylinders. This article describes the development of an experimental method for measuring friction in pneumatic lip seals. The method involves using a standard laboratory tribometer suitably equipped to reproduce as faithfully as possible the assembly and working conditions of the seals installed in a pneumatic cylinder. Since the pin-on-disk standard is generally not representative of a real application, a special pin has been developd to replicate the actual contact geometry of a seal against a barrel. If a tribometer is available, the method can be used to avoid the construction of expensive test benches and limit the time invested in testing for this type of measurement. In particular, the coefficient of friction between the seal and cylinder barrel can be measured quickly, and radial stiffness and wear damage to the seal can also be studied. Moreover, comparative friction tests were performed with a reciprocating pin-on-flat setup with the aim of studying the effect of the contact geometry and the applied load on the tribological performance of the seal.

The following sections will present the methodology and some preliminary results obtained with energised PTFE lip seals for commercial pneumatic cylinder applications.

2. Materials and Methods

The pin-on-disc method is one of the most used laboratory measurement methods for characterising materials for tribological use. The test measures the friction force generated by sliding at the contact interface between a pin at the spherical or flat end (usually stationary) installed on a sensorized arm and a flat sample (usually placed in motion). The relative motion between the pin and the sample can be either rotary or alternating linear. For the latter configuration, the test is also known as ball-on-flat (Figure 1), and the reference standard, i.e., ASTM G133, establishes the minimum specifications required for the instrument and provides guidelines for the execution of experimental measurements.

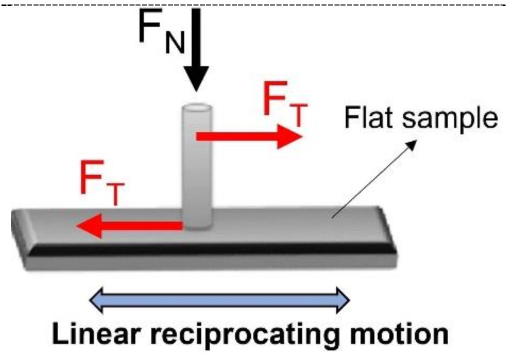


Figure 1. Ball-on-flat test setup according to ASTM G133.

However, the contact condition that is achieved by pressing a flat or spherical pin against a flat counterpart is very different from the contact geometry typical of a seal in operation: even if the same contact pressure is applied on the same materials as the actual components, the measured value of the friction coefficient may deviate from the characteristic value of the actual application [10].

A special tribometer accessory has been developed to reproduce in a simplified way a testing condition similar to the operative conditions of lip seals for pneumatic cylinders in real applications. This accessory allows testing a small circular segment of the seal cut out of the whole seal. The compact size of this configuration allows it to be mounted on a commercial pin-on-disc tribometer directly. Figure 2 shows the test setup, in which the seal-holder (3) is mounted on an Anton Paar TRB tribometer. The segment of the lip seal (1) is placed radially in contact with a portion of the barrel (2) obtained from a commercial pneumatic cylinder. The seal holder (3) is fixed to the measuring arm (4) of the tribometer, and the contact load F_N is adjusted by calibrated dead weights (5). The arm of the tribometer is sensorized and measures the friction force that develops at the seal-barrel sliding interface and is also equipped with a transducer to track the lowering of the arm (4) in the vertical direction, i.e. the vertical deformation of the lip under the action of the load along the y-axis.

The lower cylindrical sample is cut out of the barrel of a pneumatic actuator made of aluminium alloy (2). It is fixed to the sliding table (6) of the linear module of the tribometer through a dedicated fixing system (7), and the sliding table performs a linear reciprocating motion along the direction of the barrel axis (2’). During the test, the tribometer measures the instantaneous value of the coefficient of friction f as the ratio between the tangential force F_T, transferred from the seal segment to the sensorized arm (4), and the applied average load F_N.

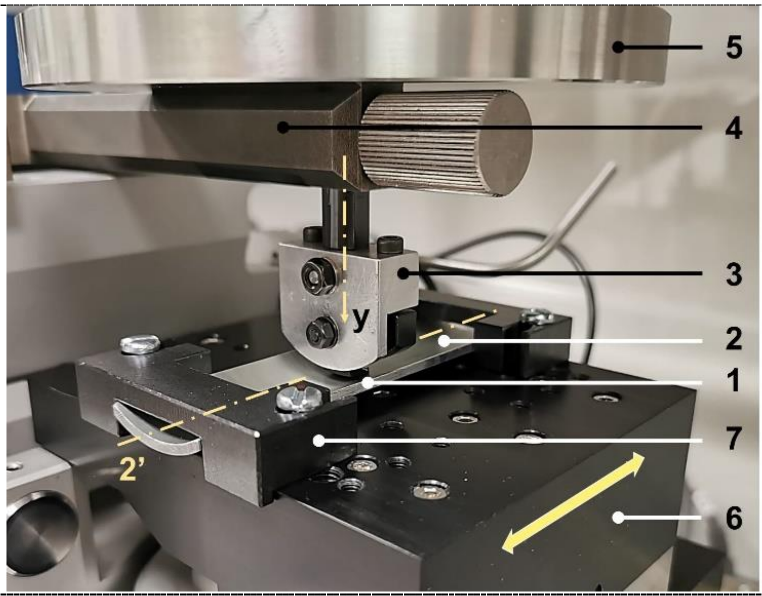


Figure 2. Special tribometer accessory for simplified friction tests with lip seals.

Figure 3 shows the side view of the seal holder (3) in which the small segment of seal (1) in contact with the lower cylindrical sample (2) is visible. The front and section views are also provided in the diagrams on the right side of Figure 3. The segment of seal (1) of length L_s = 7 mm is clamped between a cylindrical seat (3) and the fixing element (3') to replicate the mounting condition of a ring lip seal on an actual plunger. In particular, the element (3') prevents the axial displacement of the seal segment [11] and applies the radial preload experienced by the ring seal when mounted on an actual piston seat. Two segments of seals were used to carry out the tests, and at least three friction tests were run with each segment to assess the repeatability of the results. The impact of the contact pressure level on the frictional behaviour of the seal, which correlates with the vertical deformation of the lip, was investigated by raising the load from 7 N up to 10.5 N.

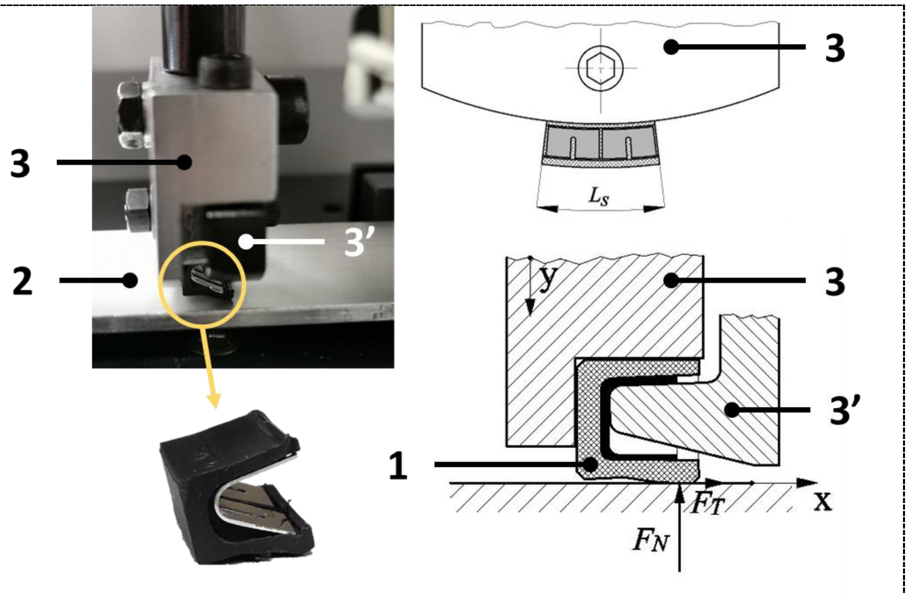


Figure 3. Figure with short caption (caption centred).

Comparative friction tests were performed with a reciprocating pin-on-flat setup (Figure 4a). A portion of the seal (1) was glued to a steel pin (2) with the flat face oriented downward (i.e., the side of the seal ring), according to the schematic in Figure 4b. The flat-ended pin thus obtained was slid against an aluminium plate (3) made of the same material as the cylinder barrel. The pin was connected to the measuring arm of the tribometer (4) through the pin-holder (5), and the contact load was applied by calibrated dead weights. Two flat-ended pins were prepared, and at least three friction tests were run with each pin to check the repeatability of the results. The impact of the contact pressure on the frictional behaviour of the material was investigated by raising the load from 22.5 N up to 33.5 N.

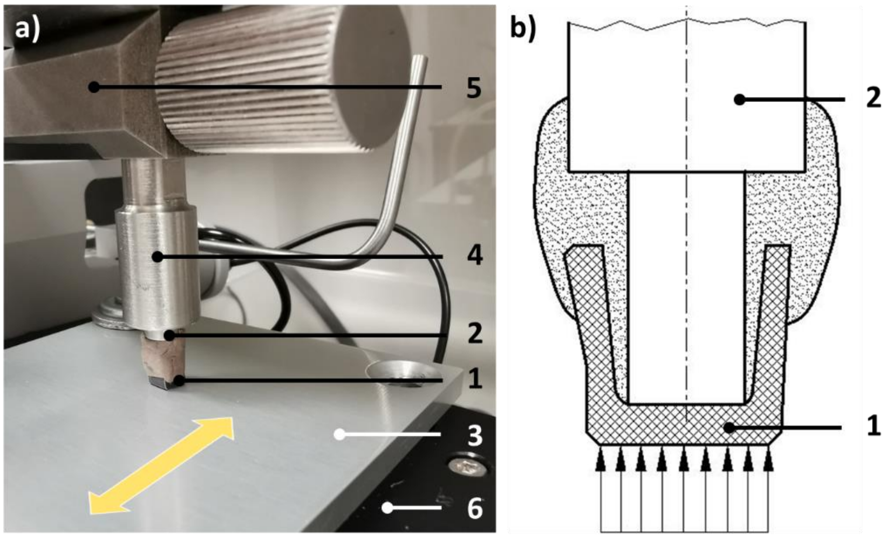


Figure 4. Pin-on-flat setup for comparative friction tests with the same material.

To compare the results of the tribological tests carried out with the special setup for lip seals with those obtained with a flat specimen of the same material, the contact load was adjusted to have a nominal contact pressure equal for the two cases.

Fuji pressure-sensitive films were used [12] to evaluate the contact area between the lip and the barrel. The sensitive film was positioned between the mating elements (see Figure 5a), and the size of the impressions was inspected under the optical microscope (Figure 5b). The nominal contact pressure was estimated as the ratio between the nominal contact area and the load F_N, assuming a uniform pressure distribution along the lip due to the limited width of the segment. The extension of the nominal contact area of the flat-ended pins was also evaluated under the optical microscope, as visible in Figure 5c. The friction tests on the flat specimen were then carried out by applying a higher contact load to produce the same nominal contact pressure as the lip seal.

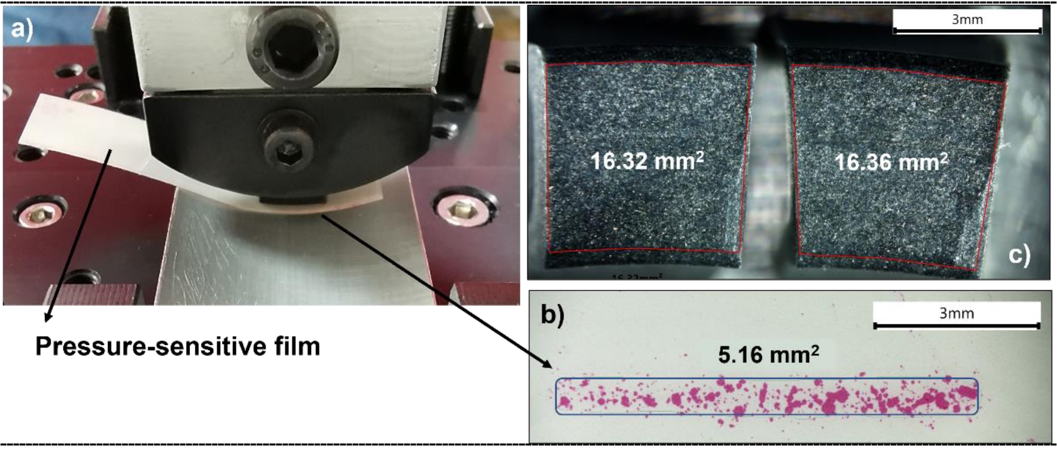
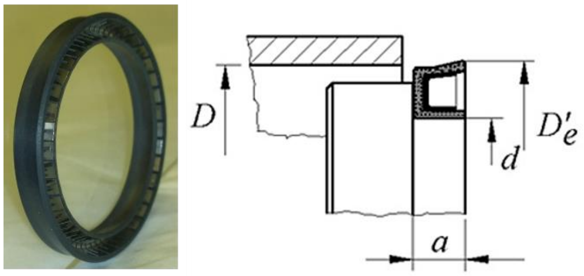


Figure 5. (a) Measurement of the contact area between the lip and the barrel through a pressure-sensitive film; (b) The resulting nominal contact area at the lip-barrel interface under 9N load; (c) The nominal contact area of the flat-ended pins.

3. Results

This section presents the results of the friction tests carried out with the two test setups described in the previous section.

The commercial lip seal used for the tests is made of graphite-reinforced PTFE and is energised with a metal foil spring. Figure 6 provides the dimensional and mounting specifications of the seal being tested, where a is the axial width, d is the diameter of the sealing seat, D_e' is the actual outer diameter of the gasket once mounted in its seat, D the diameter of the barrel and y_0 the radial interference that ensures the sealing preload on the lip. The provided values are the average measurements on three seals of the same type. The barrel diameter and the radial interference are given as characteristic intervals of the actual applications. Manufacturing tolerances of pneumatic cylinders are critical in radial lip seals as they are responsible for assembly interference, whose effects on the radial force at the interface cannot be overlooked [13-15].



	[mm]
De'	51.32
d	40.56
D	50.0 - 50.2
a	6.71
y_0	0.66 – 0.56

Figure 6. Dimensional and mounting specs of the lip seal being tested and the geometry of the related seat.

The lower sliding sample was cut out of a barrel made of aluminium alloy with a nominal diameter of 50 mm and average surface roughness *Ra* = 0.236 µm.

Before the friction measurements, static radial compression tests were performed with the seal segments to estimate the average radial stiffness *K*. The normal load F_N was increased stepwise from 5 to 10 N to obtain a radial deformation close to the typical values of y_0 reported in Figure 6. Figure 7 shows the experimental trend of the y-deformation as a function of F_N and the dispersion obtained by repeating the measurements several times with two different segments. The diagram of Figure 7 also suggests that the stiffness *K* is almost constant within the explored load range as the lip deformation increases almost linearly with increasing the load. The stiffness *K* thus evaluated represents the overall stiffness of the energised seal, which considers the contribution of elasticity of the polymeric material and the foil spring. The knowledge of the characteristic stiffness *K* of the seal is crucial for modelling the behaviour of the sealing system and the flow rate associated with leakages at the seal-barrel interface. A preliminary lumped flow model of leakages for Teflon lip seals was proposed by Raparelli et al. in [11]. In this work, the authors highlighted the need to deepen the elastic and viscoelastic behaviour of the lip since it potentially affects the contact area. However, the study of the flow rate through the seals due to leakages cannot overlook the knowledge of the friction coefficient.

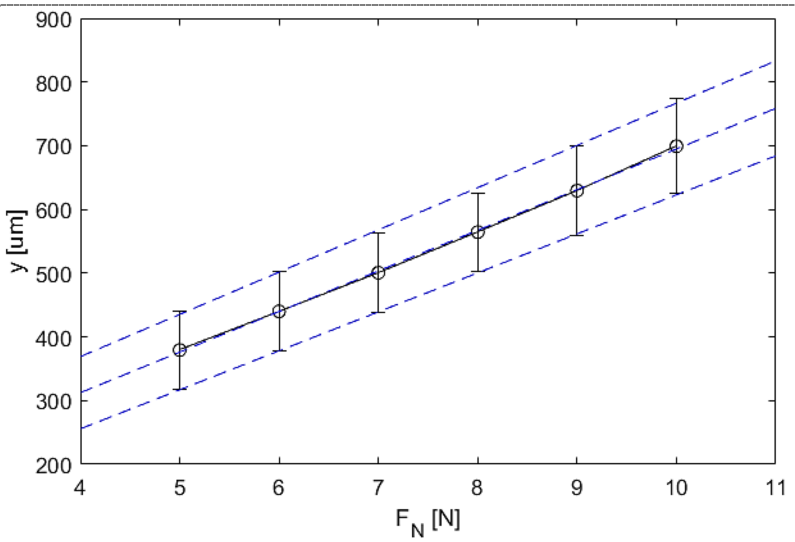


Figure 7. Deflection along the y-direction of a segment of lip seal of length L_s versus the applied load F_N on the lip.

Dynamic friction tests were performed to measure the coefficient of friction between the seal and the barrel. Tests were performed at an average speed of 0.012 m/s with both the setups described in the previous section. The aim was to verify the influence of the contact geometry on friction. The main limitation of standard pin-on-disk tests is the poor representativity of the geometric contact condition of actual components. The effect of the lip shape and the direction of motion on friction in elastomer seals was highlighted in [5, 6] through component tests carried out with a specifically developed test bench. In [16], the authors highlighted the effect of the direction of motion observed in laboratory tests performed with a reciprocating tribometer with segments of a virgin Teflon seal.

Three levels of the y-deformation of the lip seal were considered for these tests, i.e. 520 µm, 620 µm, and 720 µm. The median value was centred into the typical deformation range y_0, whereas the upper and lower values were slightly lower and slightly higher. The loads corresponding to these deformation levels were identified through the stiffness characteristic in Figure 7 and applied during the tests; the associated contact pressure levels were estimated to be equal to 1.4 MPa, 1.8 MPa and 2.2 MPa, respectively.

The same nominal contact pressure was considered for the test with the flat specimens, while the applied load was adjusted according to the larger extension of the nominal contact area. As to the tests carried out with the seal segments, a constant pressure distribution p along the contact was hypothesised due to the limited angular extension of the circular segment. It was assumed that each section of the circular segment of the seal contributes equally to the total vertical deformation, regardless of its deviation from the load axis.

In particular, these tests did not show the directional effect of motion on the friction coefficient as observed in previous tests carried out with elastomers and virgin PTFE. This evidence might be attributable to the greater stiffness of the seal under test made of graphite-reinforced PTFE compared to the elastic modulus of the materials tested in [5, 6, 16], which were one order of magnitude lower. The results of the tests are shown in Figure 8. No significant difference between the coefficient of friction obtained with the flat specimens and the seal segments was observed, and the frictional behavior was almost insensitive to the contact pressure level, at least within the range explored for this investigation. These results are in line with those observed in [11] with a full seal ring.

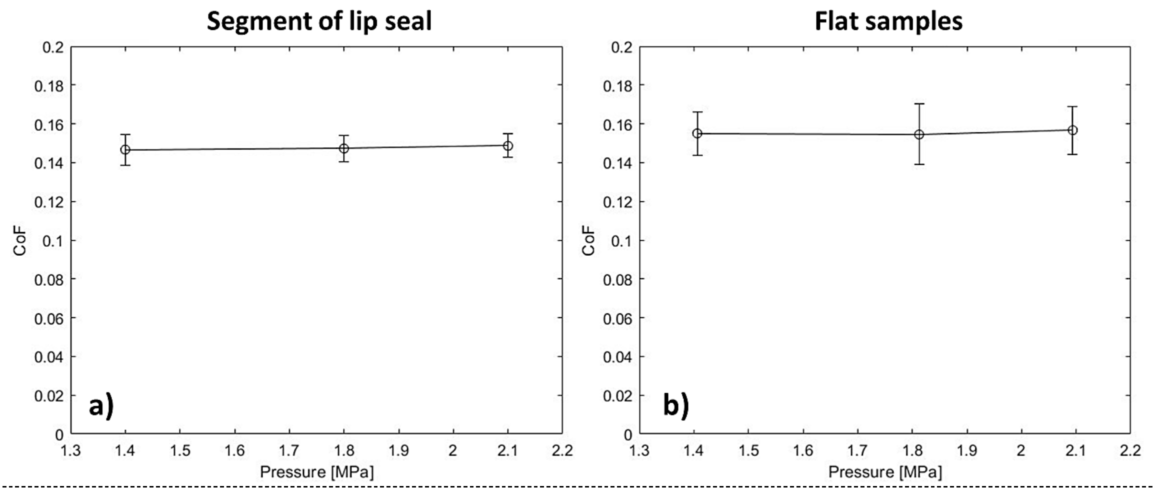


Figure 8. (a) CoF measured in tests with seal segments; (b) CoF measured in tests with flat samples.

4. Conclusion

This article described the development of a simplified experimental method for measuring friction in pneumatic lip seals where a seal segment slides against a sample of the cylinder barrel. The method involves using a standard laboratory tribometer equipped with a special device to reproduce the assembly and operating conditions of lip seals as faithfully as possible.

The preliminary results presented above prove that this method successfully replicates the tribological behaviour of seals without using specific and expensive test rigs. Static deflection tests were carried out to characterise the stiffness of the seal and determine the test load, and dynamic friction tests were performed under an increasing applied normal load to measure the coefficient of friction in case of different assembly conditions with the barrel.

The results of the preliminary tests were compared to those from standard reciprocating pin-on-flat tests with the same material to verify the influence of the contact geometry on friction. No significant difference between the coefficient of friction was observed with the two setups, and the frictional behavior was almost insensitive to the increasing contact pressure level, at least within the range explored for this investigation.

Viscoelastic properties of the plastomer material and the relative contributions from the elements of the energised seal (leaf spring, lip stiffness, contact edge stiffness) may contribute to the tribological behaviour of the seal, together with the material and roughness of the barrel. These aspects will be investigated in the future thanks to this simplified test setup. Besides, previous experimental evidence pointed out that friction may be affected by the direction of motion in lip seals. This point can also be addressed with targeted tests by exploiting this simplified method.

Besides, the fluid pressure may influence the seal deformation and the contact area, thus affecting the friction coefficient. In the future, a device able to reproduce the effect of fluid pressure on the contact mechanics of lip seals may also be developed to improve this simplified testing method further.

References

[1] Belforte, G., D’Alfio, N., and Raparelli, T., 1989, “Experimental Analysis of Friction Forces in Pneumatic Cylinders,” J. Fluid Control, 20(1), pp. 42–60.

[2] Belforte, G., Mattiazzo, G., Mauro, S., and Tokashiki, L. R., 2003, “Measurement of Friction Force in Pneumatic Cylinders,” Tribotest J., 10(1), pp. 33–48.

[3] Schroeder, L. E., and Singh, R., 1993, “Experimental Study of Friction in a Pneumatic Actuator at Constant Velocity,” ASME J. Dyn. Syst., Meas., Control, 115(3), pp. 575–577.

[4] Kazama, T., and Fujiwara, M., 1999, “Experiment on Frictional Characteristics of Pneumatic Cylinders,” 4th JHPS International Symposium on Fluid Power, Tokyo, pp. 453–458.

[5] Belforte, G., Manuello, A., and Mazza, L., 2013, “Test Rig for Friction Force Measurements in Pneumatic Components and Seals,” Proc. Inst. Mech. Eng. Part J, 227(1), pp. 43–59.

[6] L. Mazza, G. Belforte, Analytical/Experimental Study of the Contribution of Individual Seals to Friction Force in Pneumatic Actuators, Journal of Tribology, 139, 022202/1-10, 2017

[7] Wassink, D. B., Lenss, V. G., Levitt, J. A., and Ludema, K. C., 2001, “Physically Based Modeling of Reciprocating Lip Seal Friction,” ASME J. Tribol., 123(2), pp. 404–412.

[8] Salant, R. F., Maser, N., and Yang, B., 2007, “Numerical Model of a Reciprocating Hydraulic Rod Seal,” ASME J. Tribol., 129(1), pp. 91–97.

[9] Pinedo, B., Aguirrebeitia, J., Conte, M., and Igartua, A., 2014, “Tri-Dimensional Eccentricity Model of a Rod Lip Seal,” Tribol. Int., 78, pp. 68–74.

[10] Balu, J. P., “Friction Science and Technology: From Concpets to Applications”, II Ed., CRC Press, 2009

[11] T. Raparelli, L. Mazza, A. Trivella. “Experimental analysis and preliminary model of non-conventional lip seals”, Tribology International, 2023; 181: 108311 1-10.

[12] G. Belforte, M. Conte, A. Manuello, L. Mazza, C. Visconte. “Experimental and numerical

evaluation of contact pressure in pneumatic seals", Tribology International, 2009; 42: 169-175.

[13] Bulut T, Temiz V, Parlar Z. "The effect of interference on the friction torque characteristics of TPU based rotary lip seals", Tribol Ind 2015; 37: 346-353.

[14] Belforte G, Conte M, Mazza L. "Low fiction multi-lobed seal for pneumatic actuators", Wear 2014; 320: 7-15.

[15] Belforte G, Conte M, Manuello A, Mazza L. "Performance and behavior of seals for pneumatic spool valves". Trib Trans 2011; 54: 237-246

[16] T. Raparelli, L. Mazza, A. Trivella, E. Goti. "Forze di attrito in guarnizioni per cilindri pneumatici, Oleodinamica Pneumatica, 2023; 4: 44-50.