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Non contact wear measurement on pneumatic seals

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ABSTRACT
An experimental methodology aimed at the evaluation of wear in pneumatic seals is presented. New equipment was designed and manufactured in order to measure the radial thickness of worn material on the sealing edge both axially and circumferentially, by means of a laser sensor, as well as to avoid the necessity of disassembling the seals. The methodology is intended as an instrument for a quick comparison of seal prototypes and is proposed as an alternative to those methods that globally quantify the wear of samples by measuring their loss of weight or volume. Results obtained on a NBR commercial lip seal are presented.

Keywords:
Wear
Pneumatics
Seals

1. Introduction

Elastomeric seals are critical components that affect the reliability and the lifetime of almost all pneumatic and hydraulic devices involving a reciprocating or oscillating sliding motion, such as cylinders, valves, rotary and semi-rotary motors. Since friction and leakage prevention ability change during seals operations because of wear, much research has been addressed to develop wear tests for elastomeric seals, in order to quantify the amount of worn material over time. Some authors have carried out tests on flat or cylindrical elastomeric samples, made up of the same material used to manufacture commercial seals, using suited tribometers [1–3]. The influence of different parameters such as seal materials, metal counter surface roughness, lubricant and lubrication conditions on the wear process was investigated in these tests. Wear is commonly quantified by measuring the sample's loss of weight; in some cases the volume loss was determined by inspecting the wear track by a white light profilometer.

Other tests performed directly on seals were also described. A special tribometer for wear tests on lip seals of pneumatic clutch actuators, employed in trucks, was described in [4]; a part of the lip seal was assembled on a semicircular sample holder, substituting the actuator piston, and it was placed in contact with a flat sliding counter surface, substituting the actuator aluminium bore. The effect of worn particles on the wear process itself was analysed. A suitably designed test machine, able to perform wear cycles on single seals, was presented in [5]; the influence of the seal shape, material and greasing condition on types and modes of damage was highlighted. An optic method for evaluating the amount of worn material on an elastomeric seal was described in [6]; the seal modifications were monitored over time through a transparent window and recorded. In order to reproduce in-service conditions as closely as possible, other authors developed wear tests on complete components equipped with seals. A procedure for accelerating the wear process of the sliding seals mounted on a pneumatic actuator in the lab was described in [7,8]; the aim was to reproduce actual wear without modifying failure modes. The test consisted of performing complete outstroke and instroke cycles of an actuator until seals could no longer prevent leakage. After the actuator breakdown, a visual inspection of all seals was made and led to the identification of different types of damage (front seal extrusion, adhesive wear etc). An experimental methodology was developed in [9] in order to contribute to a better understanding of a typical type of seal damage, i.e. the extrusion of a seal from its seat. A test rig was specifically designed to observe and measure the seal cross-section deformation. Various parameters governing the phenomenon were identified and an empirical formula, to be used as a verification and design tool, was proposed.

The work herein presented deals with a non-contacting method for wear measurement on piston lip seals for pneumatic actuators. Tests were carried out directly on seals, without disassembling them from the piston. A testing device able to measure the radial thickness of worn material on the seal lip using a laser sensor was designed and manufactured. The methodology described in the following section is intended as an instrument for a quick comparison of seal prototypes and is proposed as an alternative to those methods that globally quantify the samples wear by measuring their loss of weight or volume; in fact, since the seal wear can be evaluated more precisely, the seal profile modification can be detected.

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2. Experimental setup and method

2.1. Experimental equipment

A previously developed test bench for accelerated life tests [3] was modified and employed to perform wear experiments on piston lip seals for pneumatic actuators ($\Phi = 50$ mm). Tests were performed on lip seals NAPN50-1, made up of NBR, in nominal mounting condi-tions. As shown in Fig. 1, seals (1) under test were mounted in suitable seats (2) obtained assembling a series of rings on the central body of a piston (3). Seals were mounted in couple, with faced lips, so as to obtain a sealed chamber (4) filled by compressed air. The convex parts of the seals were set at atmospheric pressure thanks to radial holes manufactured on the rings. Connection to the ambient was ensured by an axial hole (5) through the central body of the piston. The piston was connected to a fixed frame, while the bore (6) had a reciprocating motion, with a stroke of 500 mm. Slide rings (7) ensured a guiding surface on the bore. In order to reproduce in-service conditions, a commercial cylinder bore (6) was used, having a machining tolerance of +0,2 mm and an internal surface roughness Ra = 0.6 μm.

The test bench was designed in order to assemble two faced pistons inside the same bore. In principle, more than a couple of faced seals could be assembled on each piston. Nevertheless, preliminary experiments highlighted that increasing the number of seals under test an unacceptable increase of bore temperature due to friction was obtained. Consequently, failure modes modification could occur. For this reason, only four seals at the same time were tested.

A specific wear measuring device was developed, equipped with a laser displacement sensor; thanks to this non-contacting sensor, measurements could be performed simply taking out from the bore one piston at a time, without removing the seals from their seats. Conversely, weighting the seals would have necessarily required disassembling the seals.

A scheme of the measuring device is shown in Fig. 2(a). Element (1) had the aim of centring the measuring device on the piston; a linear precision guide (2), actuated by a micrometric screw (3), drove the axial displacement of a laser sensor (4). Consequently, the laser beam (5), perpendicular to the piston axis, could investigate the seal lip surface at various axial positions. A dividing head (6) and a dowel pin (7) were provided in order to turn the centring element (1) about the piston, so as to perform circumferential measurements. This latter degree of freedom was provided to evaluate if a uniform wear profile could be detected around the seal lip. The laser displacement sensor had a beam diameter of 0.3 mm, a measuring range of 20 mm and a resolution of 4 μm.

Fig. 2(b) shows the manufactured measuring equipment, assembled on the piston during an experimental test.

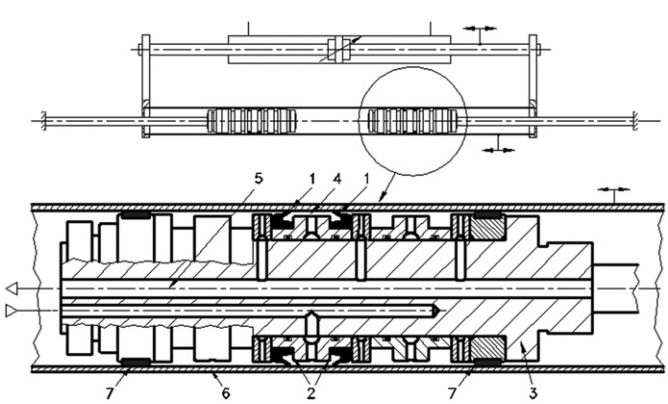

Fig. 1. Piston used as seals holder.

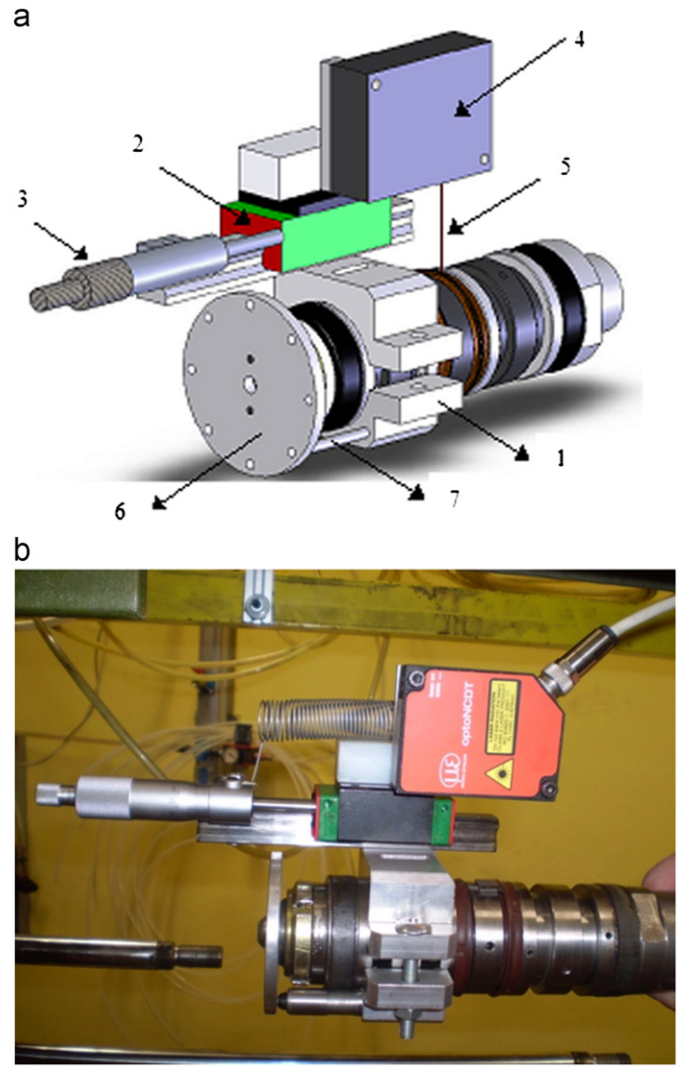

Fig. 2. Wear measuring device, equipped with a laser displacement sensor: (a) scheme; (b) manufactured equipment.

2.2. Test procedure

In order to speed up the seals wear process, tests on the accelerated life test bench were performed lubricating the piston guides with a small and known amount of semi-synthetic grease with active component PTFE (0.5 ml of Synthy Polymer 402/1). This lubrication condition allowed distributing only a thin film of lubricant between the sliding parts. A pressure of 6 bar was used for loading the seals and a relative velocity of 0.3 m/s was set between the moving bore and the fixed pistons, so as to reproduce in-service conditions. During tests, the bore temperature was monitored by thermocouples. Tests were stopped about every 80 km in order to evaluate the seals condition and to carry out wear measurement.

At first, a sealing test was performed. With reference to Fig. 1, the sealed chamber (4) was connected to a tank reproducing the volume of an actual cylinder chamber. The tank was pressurised at 10 bar and then isolated. After a defined period of time, the pressure drop due to air leakage through the seals was measured. In case of a complete empting of the sealed chamber, the seals were considered as unserviceable [10]. Conversely, if the seals were still able to prevent leakage, one piston at a time was taken out of the bore in order to carry out wear measurements.

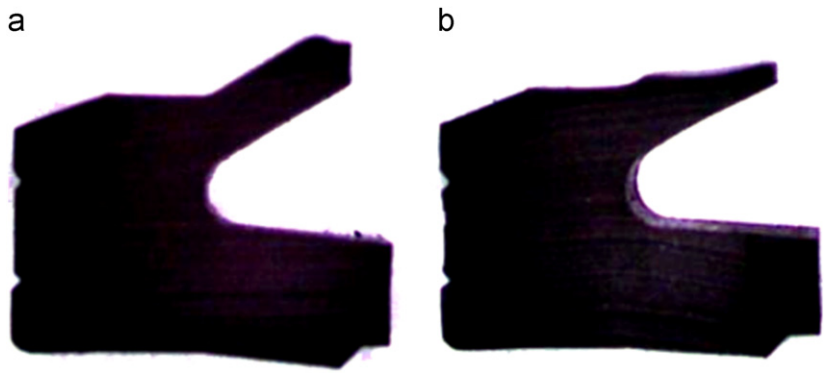

Fig. 3. Seal cross section: (a) new; (b) after accelerated life tests.

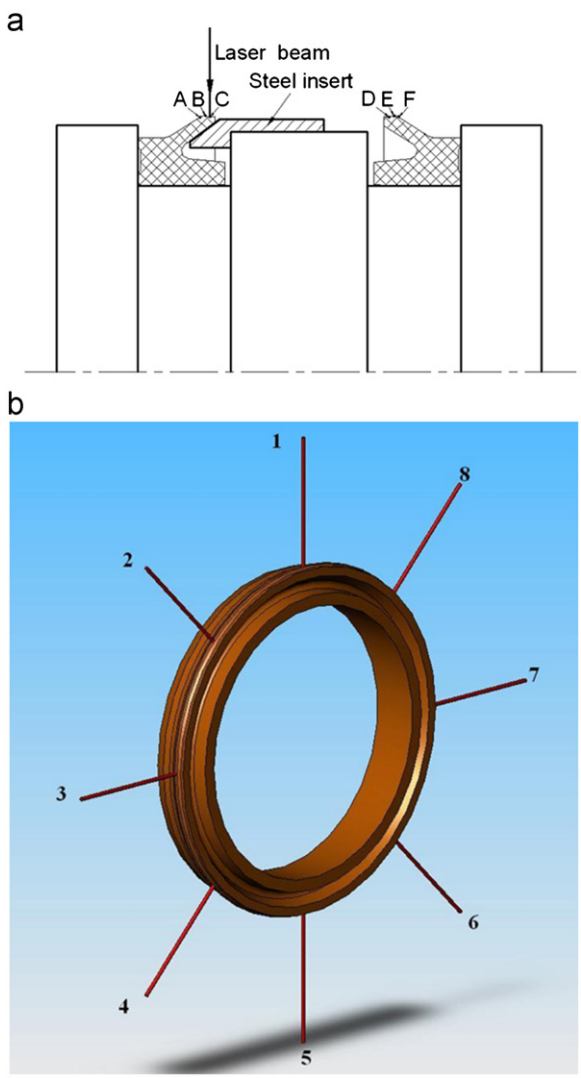

Fig. 4. Measurement points on the seal: (a) axial position on the lip profile and (b) circumferential position on the ring.

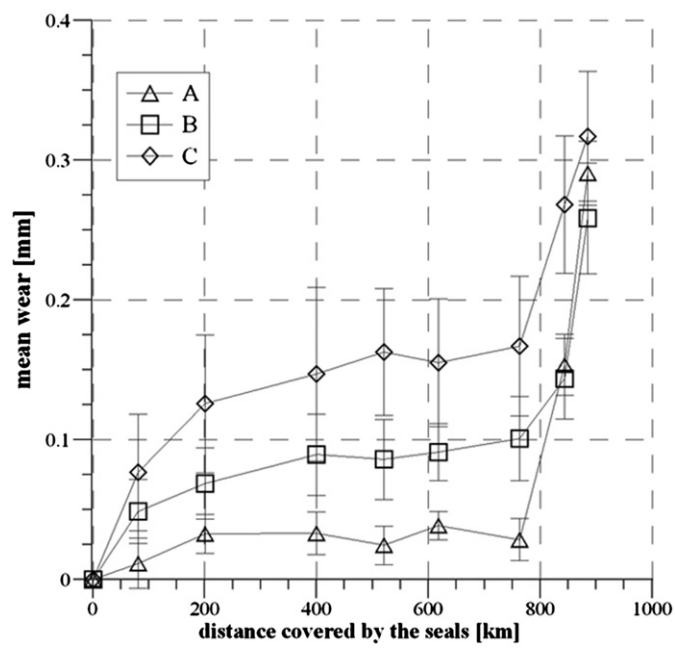

Fig. 5. Radial thickness of worn material on three axial positions on the seal lip, varying the distance covered by the seal.

The main failure mode detected during experimental tests was a lip smoothing, with a consequent loss of the sealing ability. A destructive wear with lip tearing occurred only in few cases. Fig. 3 compares the cross-section of a new seal with that of a worn seal. The worn seal lip is clearly thinner.

Test results pointed out that the radial thickness of material, removed during accelerated life tests, can be considered as a meaningful index of wear of the seal. Furthermore, this parameter can be easily associated to the air leakage.

On the basis of these remarks, the gradual increase of worn material was measured using the previously described wear measuring device. Having removed debris and grease residuals from the measuring area, a steel made insert was placed under the seal lip, as shown in Fig. 4(a). This way, despite the seal lip deformability, an unvaried initial position was ensured. Subsequently, the wear measuring device was mounted on the piston. Using the precision positioner, the laser sensor was displaced until the minimum distance between the laser emitter and the lip surface was identified and recorded. Taking the laser sensor fixed at this axial position (B, in Fig. 4), measurements were repeated circumferentially, turning the measuring equipment about the piston with an angular step of 45°. Therefore, eight points along the seal circumference were analysed at a fixed axial position, as shown in Fig. 4(b). In order to scan the seal profile axially, the same procedure was repeated placing the laser sensor at position C (0.2 mm away from position B, towards the seal lip) and at position A (0.5 mm away from position B, on the opposite side).

Tests were aimed to quantify changes in distance between the seal surface and the laser emitter during accelerated life test

cycles. For this reason, first, reference distances were measured on the unworn seal, i.e. before performing accelerated tests, following the previously described procedure. Then, measurements were repeated stopping accelerated tests. The radial amount of worn material was worked out as the difference between the actually measured distance and the corresponding reference distance.

In the following section, letters A, B, C denote the axial positions over the seal lip, independently on the seal mounting on the piston (left or right side).

3. Tests results

Fig. 5 shows the radial thickness of the worn material versus the distance covered by the seal. Each point on each curve represents the mean value calculated from thirty-two experimental data: eight values corresponding to eight circumferential points of measurement, repeated for the four seal samples assembled on the pistons. The graph refers to measurements carried out on three different axial positions on the seal lip (A, B, C); the standard deviation is highlighted.

As shown, three stages occur in the wear process: an initial stage, corresponding to the seal break-in period; an intermediate stage, approximately identified by the limits of 200 km and 800 km, during which no significant changes in wear can be detected; a final stage, close to the unserviceable state of the seal, which is characterised by a rapid increase of wear. It should be noted that the end of each curve corresponds to seal failure, i.e. the seal can no longer prevent leakage. The wear trend remains the same with varying axial positions, even if a higher wear rate was detected at the lip tip, with a higher standard deviation.

It should be noted that modifications in the seal dimensions may be due to not only the wear of seal but also the oil adsorption of the elastomer or the extraction of elastomer's constituents in presence of the lubricant. Discerning between these effects and simple wear is not possible neither using the measuring procedure described herein nor using other methods requiring seal weighting. Nevertheless, it can be assumed that the general trend of wear is correctly detected.

The experimental data were reprocessed to analyse the circumferential distribution of wear on each seal sample. In the following graphs (Fig. 6), the initial (unworn) axial cross-section of the seal is used as a reference. For a better visualisation, the measured values were multiplied by a scale factor and only two distances covered by the seal, which were around the middle of the seal life time and near to its failure, were considered. In particular, each graph shows wear on the eight measurement points along the seal circumference, before failure.

It can be noted that, once an initial wear occurs at a certain circumferential position, it tends to progress there until the seal becomes unserviceable. Nevertheless, the angular position at which this initial wear occurs is unpredictable and independent on test conditions. Therefore, systematic errors due to the test bench configuration and to the seals' assembling can be dismissed.

During tests, the bore temperature was always monitored using thermocouples, to avoid modifications of the failure modes. An increase of the bore temperature from ambient temperature to

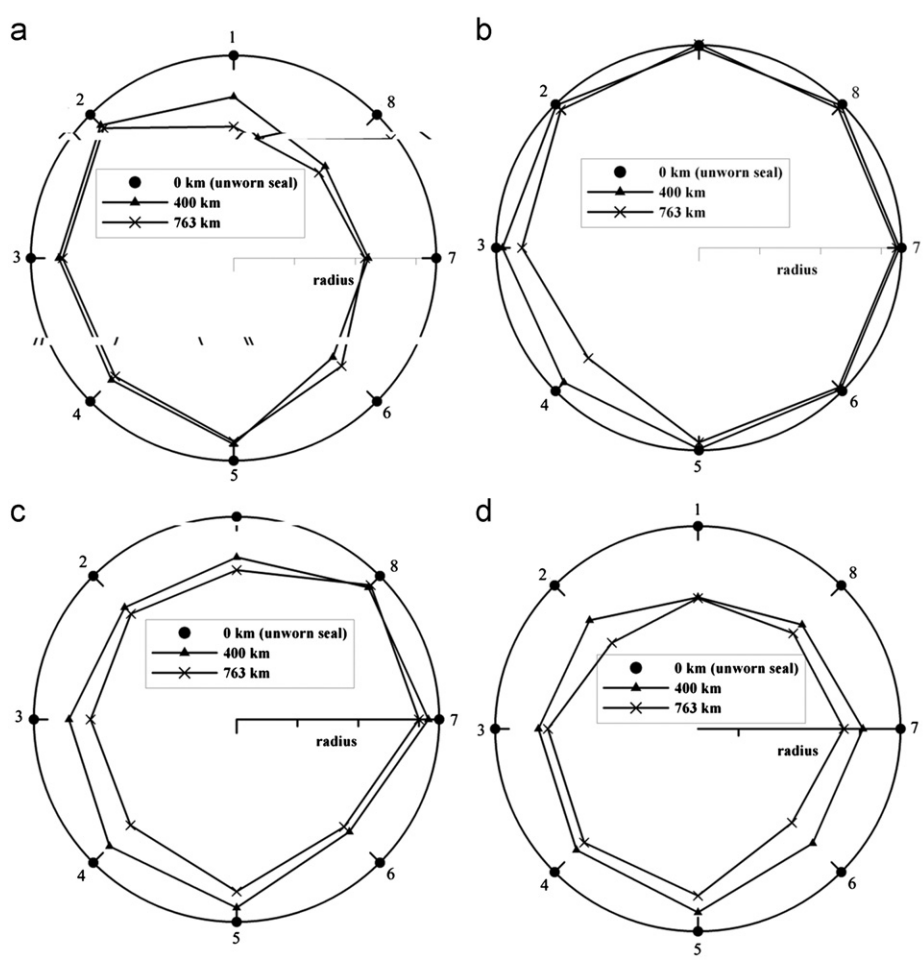

Fig. 6. Circumferential wear distribution on the axial cross-section of a seal sample: (a) position C; (b) position D; (c) position B; (d) position E.

a maximum value of about 50 °C, i.e. an acceptable range for the seal material, was detected over the test time.

4. Conclusions

The experimental methodology herein described had the aim of evaluating the wear in pneumatic seals, by scanning the seal profile in a precise way. The radial thickness of worn material versus the seal travelled distance was measured, so as to identify the lifetime of the seal and the progress of wear over time. Furthermore, the circumferential distribution of wear on each seal sample was examined. It was found that the material consumption is not uniform on the seal circumference, but it tends to occur in a certain position and to progress there, until the seal fails.

The method is intended as a kind of accelerated life test for a quick comparison of seal prototypes of differing geometries and materials. It is an alternative to those methods that globally quantify the wear of samples wear by measuring their loss of weight or volume, with the advantage of avoiding the necessity of disassembling the seals from their seats.

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