Experimental Study of Radial Lip Seals with Different Sleeve Coatings

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Abstract

Radial Lip Seals with pre-loaded garter springs of 8.5oz, 12.5oz and 14oz are tested with 4 different sleeves to investigate various seal-sleeve combinations. To find optimum sleeve coating and seal combinations, leakage and performance is investigated on an experimental test bench. This paper analyses a) Performance of various seal-shaft combinations, b) performance of varying seal pre-loaded garter springs, c) exploring the importance of a coating by comparing a stainless steel shaft to the 3 other coatings and d) integrity of sleeves after testing. Results indicate that the tungsten carbide coated sleeve outperforms the chrome oxide, hard chrome and stainless steel sleeves in terms of leakage. Chrome oxide is second in performance, third is hard chrome and the stainless steel sleeve leaked the most. Further, the tungsten carbide, chrome oxide and hard chrome sleeves are all surface finished to the desirable roughness, *Ra* = 0.2-0.4 µm while the stainless steel sleeve is not. This shows that surface coatings are significant; Vickers hardness and surface roughness of a sleeve are important factors to consider in the design process, necessary for efficient sealing. The 14oz spring, in all cases, exhibits higher leakage than the 12.5oz and 8.5oz springs. This indicates that the higher load spring results in higher wear and therefore, higher leakage. Optimum performance and lowest leakage is seen in the 12.5oz spring seal.

1 Introduction

Radial lip seals have a 1-10 µm lubricating film of liquid that separates the lip from the shaft. This film is necessary to prevent damage to the lip due to mechanical stresses and heat generation at the lip-shaft interface [1]. As shown in fig. 1, the seal consists of (1) a lip which is for sealing with the rotating shaft, (2) an outer static seal, (3) a metal reinforcement which supports the lip and (4) a garter spring which provides the pre-load on the shaft surface for sealing.

Figure 1: Radial lip seal schematic [2]

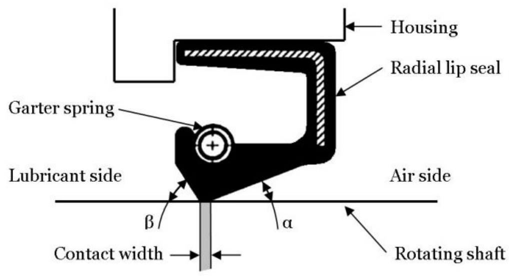


Figure 2: Radial lip seal shaft-seal interface [3]

Fig. 2 displays the seal mounted on the shaft with an interference fit. The garter spring presses down on the lip with some pressure. The pressure distribution under the lip, where it makes contact with the shaft is an important part of the sealing mechanism. The surface interaction between the shaft and the seal lip is critical, as this is where the sealing phenomenon actually takes place. Hence, the surface characteristics of the shaft and seal at microscopic levels are critical as well.

To minimize leakage, the combination of the seal surface and shaft surface must work well together. Since zero-leakage seals do not exist, the acceptable level of leakage through a seal is based on the industry and application. In the aerospace industry, the specifications of the shaft are clear in terms of surface roughness guidelines. A certain roughness is necessary for the seal to perform effectively [4].

Research continues to be carried out around how seals work and preventing undesired leakage to fill gaps in understanding sealing mechanisms [1][2][5]. However, there still is several research present on experimental works investigating the sealing mechanism of radial lip seals. In 1957, Jagger's [6] work proved the existence of a lubricant film between the lip and the shaft. Usually, anything 10 µm and less is known as a film. He noticed that the seal lubricated with oil exhibited much lower friction than seals that experienced dry friction. Further experimentation confirmed that the lubricant film remains present when the radial load of the lip on the shaft is increased. Additionally, the existence of this lubricant film in the annuli between the seal and shaft has subsequently been confirmed by many other researchers as well [7], [8].

The lip temperature is a crucial parameter that contributes to seal life as high temperatures enhanced by friction, misalignment and high rotational speeds will result in heat development. All this will limit the life span of the seal and is important to take into consideration [9].

All of these factors are effected by the seal-running surface i.e. the sleeve. It is important to note that a high quality, perfectly designed and superior seal will not perform well without the correct running surface. This includes the optimum sleeve surface finish and coating. If these factors are not included in the selection process, the PTFE radial lip seal will not seal efficiently for long periods [10]. In the work presented, the following is investigated:

a. Performance of various seal-shaft combinations by testing with 4 different sleeve coatings: tungsten carbide, chrome oxide, hard chrome and stainless steel.
b. Performance of varying pre-loaded garter springs on the lip seals: 8.5oz, 12.5oz and 14oz.
c. Exploring the importance of a coating by comparing a stainless steel shaft to the 3 other coatings.
d. Integrity of sleeves after testing.

2 Design of Test Rig

Fig. 3 below is a schematic of the test rig for this experiment. Section 1, 2 and 3 are explained below.

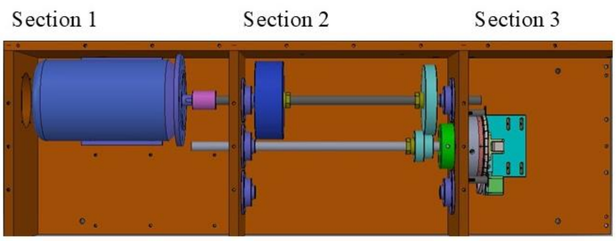


Figure 3: Test Rig Layout

Section 1 consists of the prime mover, the motor (specifications in table 1).

Table 1: Motor Specifications

Parameter	Value
Rated Power	$P_r = 2.2kW$
Poles Pair	$p = 2$
Frequency	$f = 50\ Hz$
De-rated max speed	$\omega_{max} = 3000\ rpm$

Section 2 consists of the gears transmission, input shaft and output shaft. The gears have a 1:3 ratio and there is a bearing and seal (in green) in this section to provide stability to the rig and reduce vibrations.

Section 3 is the redesigned test bench (Fig. 4a and 4b). To test different seals, the schematic consists of a stationary seal attached to the main housing. The seal is mounted on a different sleeve in each test. The sleeve is fitted to the shaft using a hydraulic coupling, clamping outward onto the sleeve and inward onto the shaft. This ensures that the sleeve will rotate with the shaft, resulting in a dynamic sealing environment. Everything is enclosed in a Perspex chamber which will be filled up with turbine engine oil, Aero shell 555, to simulate a helicopter gearbox or a bearing chamber.

There is a periscope set up with a mirror mount retainer to facilitate magnified observation of the seal-shaft interface. The mirror mount retainer is fitted onto a mount with a toothed belt. The belt is connected to a stepper motor and will rotate the mirror mount retainer slowly 360 degrees, resulting in a magnified view of the entire circumference of the seal-shaft interface. The stepper motor is a 2 phase, 4 wire cable, and bipolar motor. Its step angle is 1.8 degrees and it has a holding torque of 22 Nm. This particular set up is to observe the seal-shaft interface across the entire circumference with a high speed camera while the test is being conducted. This facilitates a better view as the entire rig is covered during operation. Further, the pattern and timing of leakage can be better observed in this manner.

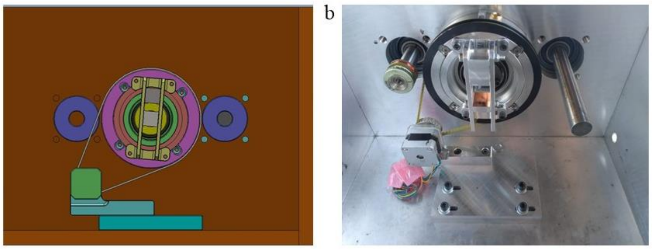
a b


Figure 4: (a) Schematic of section 3 of the test bench. (b) Image of section 3 on the test bench.

In this application, seals are placed in the input and output housing of the gearbox. In terms of rotational speed this varies according to the location of the seal in the gearbox. For example in some cases, the engine input speed is approximately 6,250 rpm on a Ø 66 mm shaft (21.6 m s-1 seal surface speed) and the main rotor output is approximately 330 rpm on a Ø 275 mm shaft (seal surface speed 4.8 m s-1). For the purpose of this study, seal surface speeds between 5-20 m/s are considered with 360 rpm – 6000 rpm on the output shaft.

The highest frequency of the motor is 50 Hz on the input shaft, which is 3000 RPM. The gears connecting the input and main shaft have a ratio of 1:3. Hence, the highest speed on the main shaft is 9000 RPM. Further, the motor is a 2 pole motor (table 1). These calculations are done using equations 1, 2 and 3 and are referred to in table 4.

$$rpm\ on\ output\ shaft = RPM\ on\ input\ shaft \times 3 \qquad \text{Equation 1}$$
$$rpm\ (n) = f\left(\frac{2}{p}\right) \times 60 \qquad \text{Equation 2}$$
$$rpm\ on\ output\ shaft = f \times 60 \qquad \text{Equation 3}$$

Hence, we will only use the motor at a maximum frequency of ~ 33.3 Hz, yielding ~2000 rpm on the input shaft of the test rig and ~6000 rpm on the main shaft of the test rig.

3 Materials

Seals: Radial lip PTFE oil seals with three different springs 8.5oz, 12.5oz and 14oz are used in this experiment. The stationary seal is mounted on the sleeve with an interference fit, connected to the main housing and does not rotate.

Sleeves: Sleeves are used for testing as it is economically and logistically more feasible to surface treat small sleeves rather than entire shafts. The sleeves will be mounted on the shaft and rotate with it. The coatings on the sleeves along with the surface profile and manufacturing methodology determines the performance of the seal. The different types of coatings tested in this work are:

a. Hard chrome: Commonly used in aerospace applications. However, industry is moving away from this as it polishes in overtime with high fatigue and wear [11].

b. Chrome oxide: A common shaft coating used in many industries, especially aerospace.

c. Tungsten carbide: Also known as hardide coatings and are increasingly popular as they do not polish in over-time, maintain their surface roughness. They also offer improved wear and fatigue over other coatings.

d. Stainless steel: This represents a plain stainless steel shaft.

All sleeve coatings are tested to study their performance with the PTFE lip seal with 3 loaded springs.

Lubricant: Aeroshell 555 is the lubricant of choice for this study as it is a standard gearbox turbine engine oil that is compatible with several helicopters [12].

4 Research Methods

Leakage of oil through the seal is measured to find the leakage rate for each seal and sleeve combination. A drip tray is set up to collect oil that leaks and is measured using a syringe. The standard acceptable limit of leakage in aerospace applications is known to be 1 ml/hour.

4.1 Hardness testing

Prior to the experiment, all sleeves are tested for Vickers hardness. This test is conducted with a pyramid hardness-testing machine. Most specimens come with a range of specified hardness values and this range can be large. The purpose of this test is to find out the exact hardness value of the specimen and to ensure it falls within the range. Table 2 shows the Vickers hardness of all 4 sleeves used in this test.

Table 2: Sleeve Vickers Hardness (units: VH)

Coating	Vickers Hardness
Hard chrome	450
Chrome Oxide	460
Tungsten Carbide	1000
Stainless Steel	250

The VH of the tungsten carbide coating is the highest at 1000 VH, whereas the hard chrome and chrome oxide coatings have a VH approximately half of that, at 450 VH. Lastly, the stainless steel sleeve has a VH a quarter of the tungsten carbide coating, at 250 VH.

4.2 Surface roughness

A Zeta-20 benchtop optical profiler is used to carry out the surface roughness and topography measurements for this work. It is a fully integrated optical profiling microscope, powered by ZDot™ technology, which simultaneously collects high-resolution 3D data and a True Color infinite focus image [13].

The surface roughness parameters of the sleeves are shown in table 3. All sleeves were manufactured for the purpose of this test. The tungsten carbide, chrome oxide and hard chrome sleeves were surface coated and treated to the desired roughness parameters. The stainless steel sleeve was left uncoated and did not have a specific surface roughness, representing a standard stainless steel shaft.

Table 3: Sleeve Surface Roughness (units: µm)

	R_a	R_p	R_v
Hard chrome	0.174	1.115	0.585
Chrome Oxide	0.135	1.699	1.115
Tungsten C.	0.187	0.471	0.689
Stainless Steel	3.143	4.145	2.178

The *Ra* of the hard chrome, chrome oxide and tungsten carbide sleeves fall within the desired surface roughness parameters *Ra* = 0.1-0.2 µm. The stainless steel sleeve has a ‘rougher’ surface that has not undergone any specific surface treatment or coating.

4.3 Rotational Speeds

Shaft speeds of 360 to 6000 RPM are tested to replicate similar conditions that the seals undergo in industry (table 4).

Table 4: Testing Speeds from 360 to 6000 rpm

Frequency (Hz)	Input shaft	Output shaft
2	120	360
3	180	540
5.5	330	990
7	420	1260
10	600	1800
15	900	2700
20	1200	3600
25	1500	4500
30	1800	5400
33.3	1998	6000

A standardized test procedure is used for uniformity amongst all tests. Each seal-sleeve combination runs for a total of 4 hours. Each rotational speed is run for a duration of 20 minutes until all the speeds have been tested (total of 3 hours and 20 minutes). Lastly, the test is left to run at 4500 RPM for the remaining 40 minutes, completing 4 hours of testing.

5 Results and Discussion

5.1 Performance of the seal-sleeve combination

Results for leakage of seal-sleeve combinations are presented in table 5. Between the 3 spring loads, the 12.5oz seal (standard issue seal) had the best performance for the hard chrome, chrome oxide and tungsten carbide sleeves. There is no leakage recorded for the chrome oxide and tungsten carbide sleeves with this seal.

Overall, the 14oz seal leaked more than the 12.5oz and the 8.5oz, having the least favourable performance between the 3. Leakage was recorded for all sleeves tested with this seal. The 12.5oz seal performed second best and had no recorded leakage with the tungsten carbide sleeve.

The tungsten carbide sleeve performed the best from all 4, with no recorded leakage for the 8.5oz and 12.5oz seals and less than 1 ml/hr for the 14oz seal. Chrome oxide was second in performance with no recorded leakage for the 12.5oz seal and less than 1 ml/hr for the 8.5oz and 14oz seal. Hard chrome was third in performance, having no configurations with no recorded leakage. However, all cases had less than 1 ml/hr of recorded leakage which is still within the acceptable limits. Lastly, the stainless steel sleeve case has recorded leakage between 1-1.5 ml/hr. This is the worst performing sleeve.

A comparison between the coated (hard chrome, chrome oxide and tungsten carbide) sleeves and uncoated (stainless steel) sleeves shows that the coated sleeves collectively had lower leakage and better performance over the uncoated sleeve. The significance of the coating is in its Vickers hardness and surface roughness. Surface treating the sleeve with the desired coating alters the hardness of the sleeve and allows the surface to be machined to the desired roughness as well.

1 ml/hr is the acceptable rate of leakage for seals.

Table 5: Total Leakage per hour (units: ml/hr)

Leakage Rate			
	8.5oz	12.5oz	14oz
Hard chrome	0.20	0.60	0.40
Chrome Oxide	0.78	0	0.87
Tungsten Carbide	0	0	0.50
Stainless Steel	1.05	1.5	0.925

During each 4 hr test, the speed at which leakage began is recorded in table 7. In all cases, any leakage, if present occurs after 1800 RPM. Prior to this speed, there was no leakage seen in any of the tests. This indicates leakage does not occur prior to 1800 RPM at lower speeds.

Further, from table 7 it is clear that leakage begins at the lowest recorded speed for the stainless steel sleeve. Earlier onset of leakage indicates a higher total amount of leakage recorded overtime. This is also another indicator of the low performance of this sleeve.

Table 6: Speed at which leakage begins (units: rpm)

Hard chrome	
8.5oz	2700
12.5oz	4500
14oz	4500
Chrome Oxide	
8.5oz	1800
12.5oz	-
14oz	4500
Tungsten Carbide	
8.5oz	-
12.5oz	-
14oz	2700
Stainless Steel	
8.5oz	1800
12.5oz	1800
14oz	1800

5.2 Integrity of the sleeves

The coating of the sleeve is critical in ensuring seal performance. Due to the nature of the filled PTFE, these seals can be more abrasive than standard elastomer seals. They contain glass fibres and other fillers that improve their mechanical properties considerably, reducing wear that would occur if pure PTFE were used [14].

The sleeves require a hard enough surface that will withstand the PTFE seal running on it. Most standard stainless steel shafts (series 200 and 300) would have a very low Vickers hardness of 200-300 HV or less [15] which is not ideal for the seal. A specific surface roughness is also imperative for the shaft, Ra = 0.1-0.2 µm. This is because a slightly semi rough surface aids in additional sealing mechanisms and a perfectly smooth or extremely rough shaft would not provide this [16].

The hardness of the tungsten carbide sleeve ranges between 800-1200 HV, the highest of all four sleeves. The chrome oxide coating has a 450 HV. Further, between the chrome oxide and tungsten carbide sleeves, the chrome oxide is left with a very prominent dark seal track on the running surface of the sleeve (Fig. 5a). On the other hand, the tungsten carbide sleeve did not have any such mark and remained intact (Fig. 5b). It was the best performing coating that maintained its integrity from the four sleeves tested.

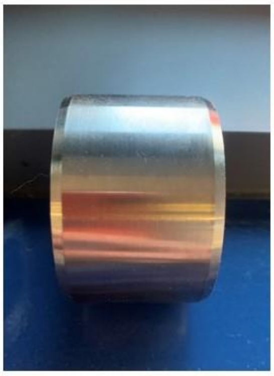
a  b 

Figure 5: (a) Chrome Oxide Sleeve with visible wear track and dark area indicating material transfer where seal is mounted. (b) Tungsten Carbide Sleeve with no visible wear track where seal is mounted.

6 Conclusions

The leakage and performance of various seal-sleeve combinations are tested in a rotating test rig simulating a helicopter gearbox. To investigate the speed at which leakage begins and the amount of leakage in each case, a range of rotational speeds are tested. Three seals with pre-loaded garter springs loads of 8.5oz, 12.5oz and 14oz are used. Four sleeve coatings are tested here: hard chrome, chrome oxide, tungsten carbide and stainless steel. Surface profile and hardness measurements of the sleeves are taken prior to the test to ensure they are within the desired ranges. Several conclusions are drawn based on the experiment.

a) The 12.5oz seal (standard issue seal) had the best performance for the hard chrome, chrome oxide and tungsten carbide sleeves. There is no leakage recorded for the chrome oxide and tungsten carbide sleeves with this seal. This indicates that the 12.5oz seal has an optimized lip pressure for a general application, neither causing excessive wear nor excessive leakage.

b) The 14oz seal leaked more than the 12.5oz and the 8.5oz, having the least favourable performance between the 3 seals. Leakage is recorded for all sleeves tested with this seal. A higher spring load results in more friction and wear and therefore, higher leakage rates as well.

c) The three specimens with coatings had better performance than the plain sleeve. Using hard, wear-resistant coatings helps improve the overall performance of the seal. They reduce leakage by preventing pre-mature wear of the seal and quality of the surface finish. With a plain stainless steel shaft, the onset of leakage is at lower speeds and results in overall higher leakage rates. This incurs maintenance costs due to early failure of components.

d) The tungsten carbide sleeve, with a VH of 1000 outperformed the remaining 3 sleeves. It maintained its integrity after the test and remained without a wear track. The chrome oxide sleeve performed second best. However, the sleeve did not maintain its integrity and is left with a black ring on its running surface where the seal was mounted.

e) There is no recorded leakage in any case below 1800 rpm. This indicates that leakage generally does not occur at lower speeds, even with poor seal-sleeve combinations. Higher speeds result in harsher environmental conditions of high temperature, friction and pressure, causing leakage in some cases.

Further work on the sleeves is being done to study why the tungsten carbide sleeve coating has maintained its integrity after testing, but the chrome oxide one has not. The coatings are applied using different techniques, resulting in varying surface topographies and properties. This will play a critical role in determining how it will interact with the seal, ultimately impacting the overall performance of the seal.

Acknowledgements

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