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Piston Rod Coating Material Study of Reciprocating Sealing Experiment Based on Sterling Seal

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Abstract: Sterling seal is a commonly used reciprocating seal, in which the PTFE ring of the seal and the surface material of the piston rod play an important role in the reciprocating sealing process. In this paper, a reciprocating sealing test bench was built, four sets of carbon fiber PTFE sealing rings were used to perform reciprocating sealing bench experiments with Cr-coated piston rods and DLC-coated piston rods. After the experiment, the used four sets of seals were taken as experimental samples, and a new, unused carbon fiber PTFE seal was taken as a reference sample. The surface topography, surface wear, and wear surface elements of the test specimens were measured by three-dimensional white light interference surface topography instrument, field emission environment scanning electron microscope, and field emission scanning electron microscope. Through experimental determination, it is found that the coating material is detached to form abrasive grains, which causes the surface of the sealing ring to wear. This paper also proposes optimization suggestions for the processing method of the sealing ring and the selection of the material of the piston rod coating.

Keywords: sterling seal; reciprocating seal; friction and wear; interface performance; coating material

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1. Introduction

Seals are key infrastructure components in many high-tech fields, including the aerospace and ergonomics industries [1–3]. The structure and performance of rubber and plastic seals are critical to the operation, performance, and service life of machinery [4]. Poor sealing performance not only increases the friction, wear, and power consumption of the machine, but also shortens the working life of the machine, and also causes environmental pollution and equipment corrosion due to leakage. The failure of the seal will directly affect the efficiency of the whole machine, resulting in a large number of economic losses, and even lead to serious safety accidents [5]. In the field of aerospace engines, seals are constantly subjected to severe working conditions that include high temperatures, high pressures, and strong vibrations.

The hydraulic reciprocating seal device is a key basic component of modern mechanical equipment. The research on reciprocating seal began before World War II [6], and the early research on the reciprocating seal was mainly based on experimental research. With the continuous improvement of hydraulic device performance, researchers began to quantitatively measure and analyze system friction. In 2012, Crudu and Fatu [7] compared the friction force calculated by the numerical value with the friction force measured by the experiment, and the friction force measurement device of the reciprocating seal system adopted a vertical structure. The friction force of the reciprocating sealing system was measured by the tension and pressure sensor installed on the piston rod. Wu Qiong [8] studied the friction characteristics of nitrile rubber O-rings in the reciprocating seal system under different working conditions through experiments and obtained the influence of different oil pressure, speed, lubricating medium, and other parameters on the friction performance.

In response to the problem of seal wear, the researchers have achieved a series of research results after more than half a century of research. Such as the establishment of the seal elastohydrodynamic lubrication model to evaluate the performance of the seal, study the seal failure mechanism, and improve the seal ring structure and materials to improve the life and reliability of the seal [9–20]. Guo Fei [21,22] used the combination of theoretical analysis, numerical simulation, and experimental measurement to carry out the research on the dynamic evolution law of lip seal performance. The research results are the premise and basis of failure mechanism research and life prediction. Chang Kai [23] based on the ARCHARD friction and wear model using ANSYS structural analysis and thermal analysis function, proposed a calculation method for O-ring wear simulation, and combined with the engineering practice, the basis for judging the wear failure of the O-ring is proposed. In the research process of the reciprocating seal, researchers generally believed that the failure of the reciprocating seal was caused by the wear of the seal ring. In addition, most of the subsequent experimental studies by researchers have studied the influence of changes in oil pressure, reciprocating speed, temperature, and seal ring structure size on the wear of the seal ring. In 2011, Ye Sujuan [24] analyzed the wear conditions of commonly used PTFE at different temperatures, she concluded that PTFE filled with carbon-filled graphite has a lower friction coefficient and stronger wear resistance than PTFE filled with bronze powder and carbon fiber at high temperatures. In 2015, Zheng Jinpeng [25] conducted friction and wear experiments on nitrile rubber and stainless steel materials and studied the effect of hard particles on the friction coefficient and wear of nitrile rubber. Wu Changgui [26] combined with theoretical analysis and experimental measurement, carried out research on sealing and interface modification methods under high pressure, and explored methods and means to ensure sealing life.

However, in reciprocating seal experimental research and friction and wear research, most of the experimental research by researchers have studied the effects of changes in oil pressure, reciprocating speed, temperature, and seal structure size on the wear of the seal [27–29], the effect of the sealing ring processing technology and the piston rod coating material on the wear of the sealing ring is rarely considered.

In this paper, a reciprocating sealing test bench was built. The sealing rings with carbon fiber PTFE were added to the reciprocating sealing bench experiment with the chrome-coated piston rod and the DLC-coated piston rod. After the experiment, the used sealing rings were taken as the experimental samples. The surface morphology, surface wear and wear surface elements of the samples sealing lips were measured by three-dimensional white light interference surface topography instrument, field emission environment scanning electron microscope, and field emission scanning electron microscope. Through experimental determination, it is concluded that the coating material is detached to form abrasive grains, which causes the surface of the sealing ring to wear. The optimization of the processing technology of the sealing ring and the selection of the material of the piston rod coating is proposed.

2. Materials and Methods

2.1. Materials

2.1.1. Seals

The reciprocating sealing experiment was carried out using the stepped ring GMSS for the heavy-duty shaft purchased by the Seal Research Institute of Guangzhou Mechanical Science Research Institute Co., Ltd. The sealing rings are all sterling seal, as shown in Figure 1. The seal is composed of a D-ring and a wear-ring. The structure and installation dimensions are shown in Figures 2 and 3, and Table 1. The D-ring material is nitrile rubber, and the wear-ring material is PTFE filled with carbon fiber (the filling ratio is about 15%). The PTFE and fillers are mixed in a high-speed mixer and then molded at ambient temperature. Later sintering was carried out, and finally, seals are made by turning processing.

Figure 1. Sterling Seal.

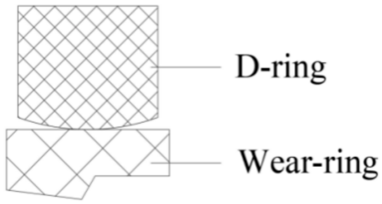


Figure 2. The sectional view of the sterling seal.

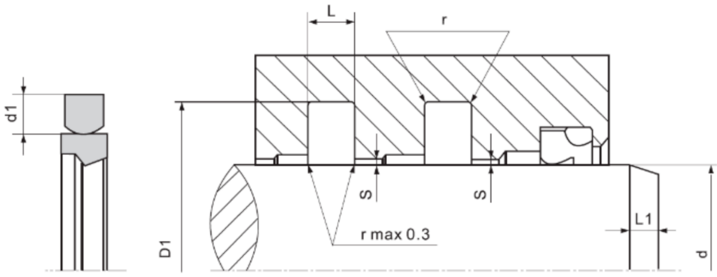


Figure 3. Installation diagram of sealing ring sterling seal.

Table 1. Step size GMSS installation dimension table for heavy-duty shaft.

Rod Diameter df8/h9	Bottom Diameter D1 H9	Groove Width L + 0.2	Mounting Chamfer L	Fillet r	S max		
					10 Mpa	20 Mpa	40 Mpa
50	50 + 15.0	7.5	5.0	0.3	0.50	0.40	0.30

2.1.2. Piston Rod

The coated piston rod used in the experiment was processed by Wuhu Yinhong Hydraulic Parts Co., Ltd., Wuhan, China. The two-piston rod base materials used in the experiment are stainless steel, which were respectively coated with different coatings. One piston rod was chrome-plated on the steel surface, and the other piston rod was plated with DLC (diamond-like) film on the surface. The surface of the piston rod was plated with Cr by electroplating, and the thickness of the coating was about 50 µm. Using conventional physical weather deposition (PVD) technology, the thickness of the coating is about 10 µm.

2.1.3. Lubricating Oil

Kunlun 15# aviation hydraulic oil produced by China National Petroleum Corporation is used as lubricating oil, its characteristics are shown in Table 2.

Table 2. Kunlun 15# aviation hydraulic oil.

Item		Index
Appearance		Red transparent liquid
Kinematic Viscosity (mm^2/s)	100 °C	5.306
	40 °C	13.84
	−40 °C	383.2
	−54 °C	1456
Flash Point (°C)		104
Condensation Point (°C)		−74
Density (20 °C) (kg/m^3)		839.3

2.2. Experiment of Reciprocating Sealing

The friction between seals and piston rod can be measured through experiments [30]. First, we designed and built a reciprocating seal test bench. The structure of the reciprocating sealing test bench is shown in Figure 4. It was mainly composed of hydraulic cylinder, piston rod, tested sealing ring, and tension and pressure sensor. During the experiment, the piston rod is fixed, and the hydraulic cylinder is reciprocated by the driving cylinder to supply oil on the fixed track. The hydraulic cylinder is supplied with oil from the oil supply station to achieve the experimental oil pressure in the cylinder, and the pressure value data is collected by the tension and pressure sensor. The reciprocating test bench is controlled by the control panel. According to the signal of the sensor, the signal processing is performed to obtain the sum of the friction between the front and rear sealing rings and the piston rod, thereby calculating the friction between the single sealing ring and the piston rod.

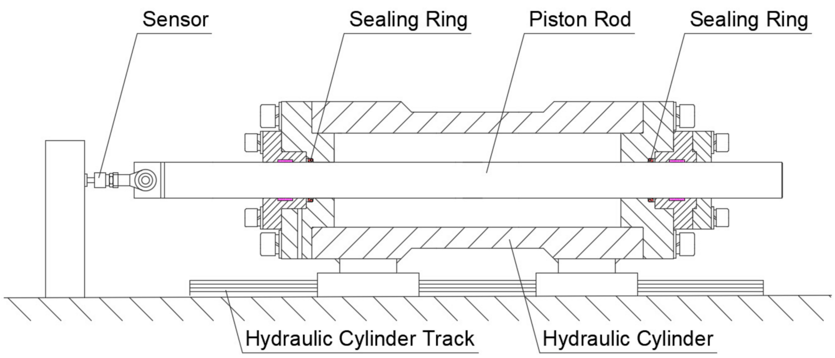


Figure 4. Schematic diagram of the reciprocating sealing test bench.

Figure 5 is a physical diagram of the hydraulic cylinder of the reciprocating sealing test bench, in which a drive cylinder drives a hydraulic cylinder to perform a reciprocating motion. Figure 6 is a physical diagram of the gas station and the drive station of the reciprocating sealing test bench. Figure 7 is a physical diagram of the control panel of the reciprocating sealing test bench.

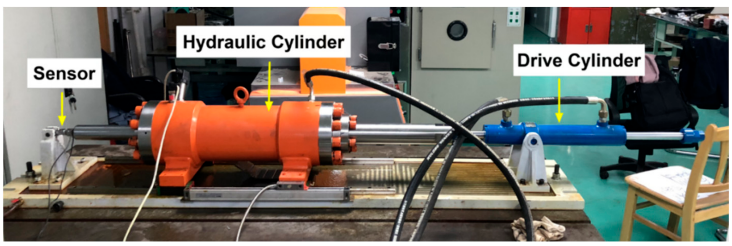


Figure 5. Reciprocating seal test bench hydraulic cylinder physical diagram.

Figure 6. Reciprocating seal test bench drive station and gas station physical diagram.

Figure 7. Reciprocating sealing test bench control panel physical diagram.

The experimental temperature was 20 °C. The experimental set oil pressures were 10 MPa, 20 MPa, 30 MPa, and 35 MPa, and the reciprocating speeds were set to 100 mm/s, 200 mm/s, 300 mm/s, 400 mm/s, and 500 mm/s. The number of reciprocating times per experiment was set to 300, and the sampling rate of the tension and pressure sensor was 2.4 kHz. According to the test bench design, two seals were required for each experiment, so four pairs of seals were selected and divided into two groups for reciprocating experiments. According to different experimental piston rod coating materials, each set of seals was tested twice: first, two new Sterling and Cr-coated piston rods were used for the experiment; second, two new Sterling seals and a DLC-coated piston rod were used for the experiment.

2.3. Interface Measurement Methods of Sealing Lips

Studying the morphology and contact conditions of friction surfaces are the basis for analyzing friction, wear, and lubrication problems in tribology. Any friction surface is composed of many different shapes of micro convex peaks and concave valleys. Surface aggregation characteristics play an important role in friction, wear, and lubrication in mixed and dry friction conditions [31].

In the reciprocating sealing system, the friction is generated by the reciprocating motion, friction and wear are inevitably caused to the two objects in relative motion- seals and piston rod. Through the experimental measurement of the friction force mentioned, the friction force of the reciprocating seal of the piston rod of different materials and different coating materials can be obtained. According to the friction force and the leakage of the system, a material with better sealing performance can be selected in theory. However, the friction force does not fully reflect the degree of wear of the sealing system. As the degree of wear increases, the sealing performance of the seal will decrease and its life will be greatly shortened. Therefore, this article will conduct an experimental test on the sealing ring lip from the surface microscopic view, analyze the wear degree of the sealing ring lip by the different material coating materials of the piston rod, and select the piston rod coating material with the better sealing performance [5].

The tribological phenomenon occurs on the surface layer, so the change of the surface structure is the key to the study of friction and wear laws and mechanisms. The application of advanced instruments and equipment can be used to study the phenomenon of friction surfaces [31]. In this article, the test samples of the seals were used in the reciprocating sealing bench test, the surface morphology, surface wear and wear surface elements of the samples sealing lips were measured by three-dimensional white light interference surface topography, field emission environment scanning electron microscope and cold field emission high-resolution scanning electron microscope.

2.3.1. Experimental Samples

After the reciprocating sealing frame was completed, the test bench was disassembled. We took out the used seal as the experimental samples of the subsequent experiment, and selected 1 sealing ring for each experiment (4 in total). Another new, unused seal was taken as a reference, and the inner ring of the seal with a length of about 5 mm was cut for use. The sample names and labels are shown in Table 3, and the experimental samples were shown in Figure 8.

Table 3. Samples names and labels.

	Contact with Cr-Coated Piston Rod	**Contact with DLC-Coated Piston Rod**
First Experiment	Cr-1	DLC-1
Second Experiment	Cr-2	DLC-2
New Seal	New	

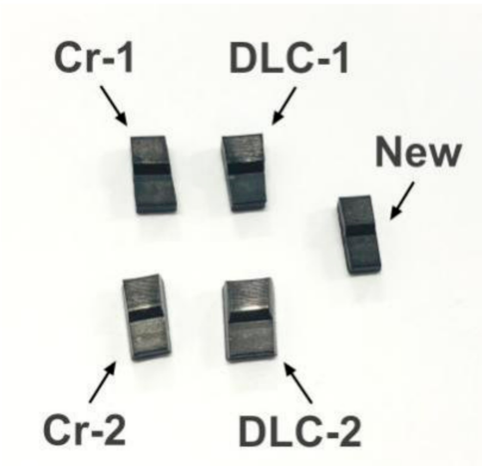


Figure 8. Surface element determination experimental samples.

2.3.2. Determination of Surface Morphology of Sealing Lip

The Nexview three-dimensional white light interference surface topography instrument of the National Key Laboratory of Tribology of Tsinghua University was used to determine the surface topography of the inner lip of the seal.

The experimental sample was fixed on the test bench, the appropriate lens was selected, the magnification is adjusted to 50 times, the sample position was adjusted, and the inner sealing lip of the sealing ring and the shaft contact area (about 800 µm in width) were selected for measurement.

2.3.3. Determination of Surface Wear of Seal Lip

Surface wear measurement of the inner lip of the seal ring using field emission environment scanning electron microscope of the State Key Laboratory of Tribology, Tsinghua University.

We placed the experimental samples into the experimental instrument, aligned the lens with the inner lip and the shaft contact area of the sealing ring, adjusted the lens position, selected the visible range, and selected the magnification multiples of 200 times, 500 times, and 1000 times for the experimental determination.

2.3.4. Determination of Wear Surface Elements of Sealing Lips

The surface elements of the wear lip on the inside of the seal were measured by field emission scanning electron microscope of the State Key Laboratory of Tribology, Tsinghua University.

We placed the experimental sample into the experimental instrument, aligned the lens with the inner lip of the sealing ring and the contact area of the piston rod, adjusted the lens position, selected the visible range, and selected the magnification of 500 times for the experiment. Since the two used seal rings were in frictional contact with the Cr-coated piston rod and the plated DLC-coated piston rod, the dual materials were Cr and C, and the coated piston rod base body was made of stainless steel. Therefore, the measurement elements were Cr, C, and Fe.

3. Results and Discussion

3.1. Reciprocating Sealing Experimental Data Processing and Analysis

According to the experimental operation, the readings of the tensile and pressure sensors under different experimental sample materials, oil pressure, and reciprocating speed were recorded. The changing trend of the friction force with the oil pressure and the reciprocating speed were obtained. Figure 9 is the raw data of a reciprocating experiment of a carbon fiber-filled PTFE sealing ring and a DLC-coated piston rod at 10 MPa and 100 mm/s. In the raw data, the friction is the sum of the reciprocating friction between the two seals and the piston rod.

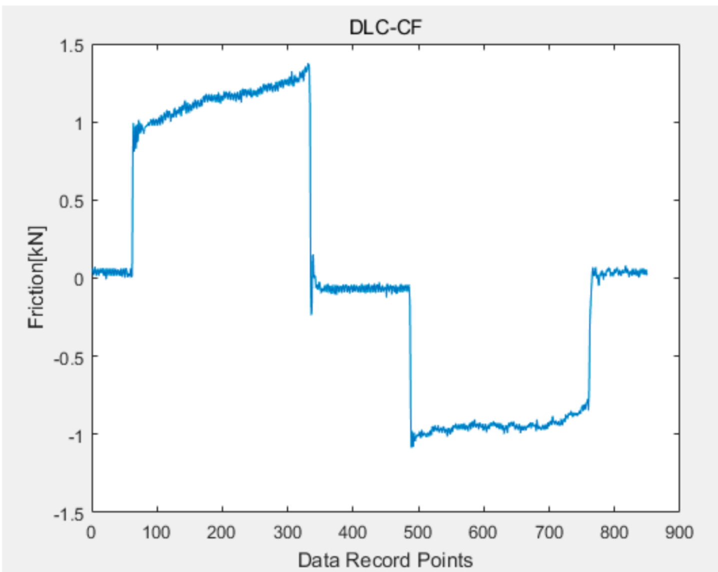
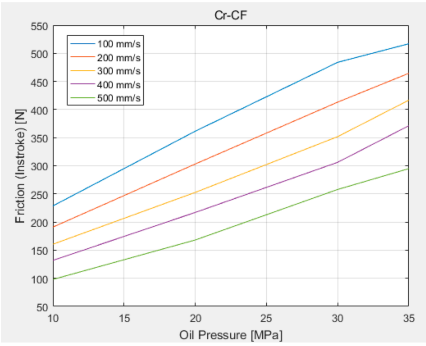


Figure 9. Reciprocating experiment friction measurement raw data.

Take the smooth data of the middle section of instroke and outstroke, and use Matlab software for data processing to obtain the frictional force of a single seal ring of instroke and outstroke under different oil pressures and different reciprocating speeds. The friction between each set of sealing ring and the piston rod is taken as the average value of the two experiments, and the data is analyzed to obtain the frictional change law between the sealing ring and the chrome-coated piston rod and the DLC-coated piston rod.

3.1.1. Analysis of Friction between Seal Ring and Chrome-coated Piston Rod

Figure 10 shows the frictional force as a function of oil pressure at a given speed. It can be seen from Figure 10 that when the reciprocating speed is constant, the frictional force of instroke and outstroke increases with the increase of the oil pressure, and the growth trend is obvious. And at the same oil pressure, the friction force under high-speed conditions is greater than the friction force under low-speed conditions.



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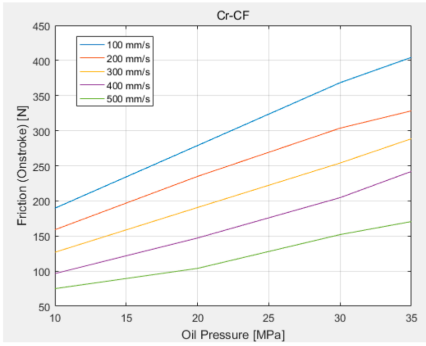
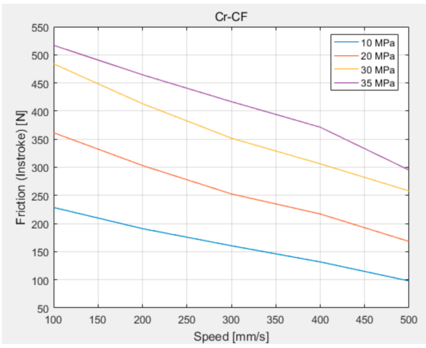


(**b**)

Figure 10. Cr-CF hydraulic pressure-friction diagram: (**a**) Instroke; (**b**) Outstroke.

Figure 11 is the schematic diagram showing the change of friction with speed when the oil pressure is constant. It can be seen from Figure 11 that when the oil pressure is constant, the frictional force decreases as the speed increases. And at the same reciprocating speed, the friction under high-pressure conditions is significantly greater than the friction under low-pressure conditions.



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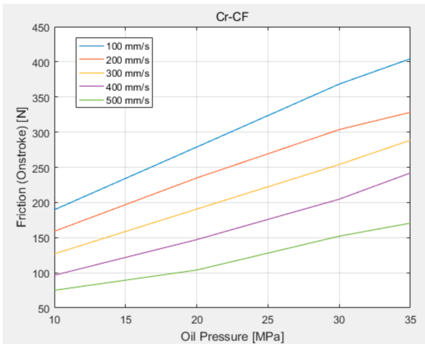
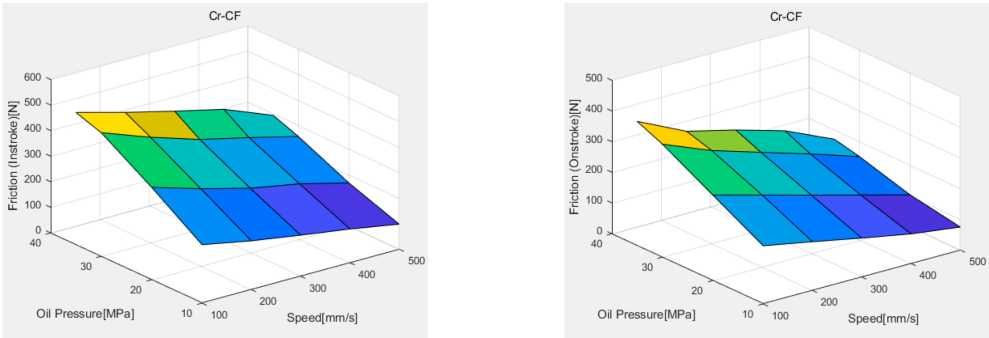


(**b**)

Figure 11. Cr-CF hydraulic speed-friction diagram: (**a**) Instroke; (**b**) Outstroke.

Figure 12 shows the three-dimensional diagram of the frictional force as a function of oil pressure and velocity. It can be seen from Figure 11 that the friction is the smallest when the minimum oil pressure is maximum (10 MPa, 500 mm/s), the pressure in instroke is 97.8955 N, and in outstroke is 75.0238 N. The friction is the largest when the oil pressure is the highest and the speed is the smallest (35 MPa, 100 mm/s), the pressure in instroke is 516.9906 N, and in outstroke is 404.4382 N.

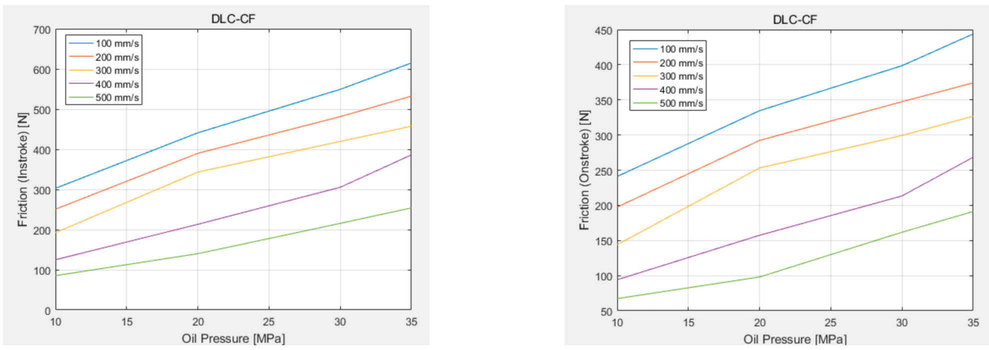


(**a**) (**b**)

Figure 12. Cr-CF pressure-speed-friction three-dimensional diagram: (**a**) Instroke; (**b**) Outstroke.

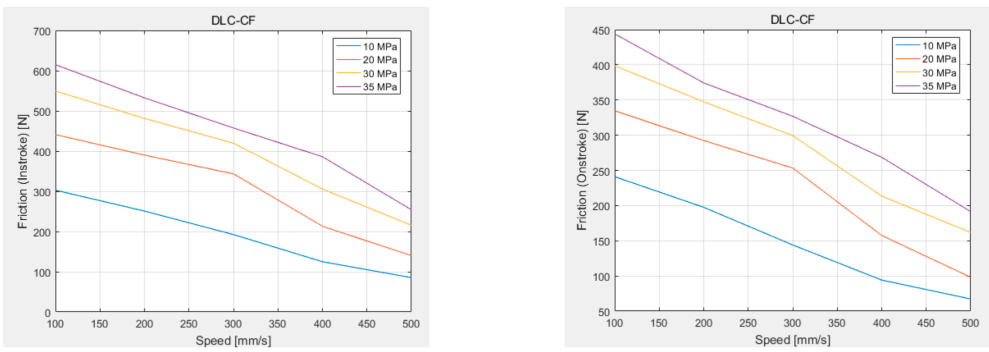
3.1.2. Analysis of Friction between Seal Ring and DLC-coated Piston Rod

It can be seen from Figures 13 and 14 that the frictional force measured by the sealing ring in contact with the DLC-coated piston rod is consistent with the changing trend of the frictional force measured by the sealing ring in contact with the chrome-coated piston rod. Figure 15 shows the three-dimensional diagram of the frictional force as a function of oil pressure and velocity. It can be seen from Figure 15 that the friction is the smallest when the oil pressure is the smallest and the speed is the highest (10 MPa, 500 mm/s), the pressure in instroke is 85.3296 N, and the pressure in outstroke is 67.2692 N. The friction is the largest when the oil pressure is the highest and the speed is the smallest (35 MPa, 100 mm/s), the pressure in instroke is 614.8485 N, and the pressure in outstroke is 443.8553 N.



(**a**) (**b**)

Figure 13. DLC-CF hydraulic pressure-friction diagram: (**a**) Instroke; (**b**) Outstroke.



(**a**) (**b**)

Figure 14. DLC-CF hydraulic speed-friction diagram: (**a**) Instroke; (**b**) Outstroke.

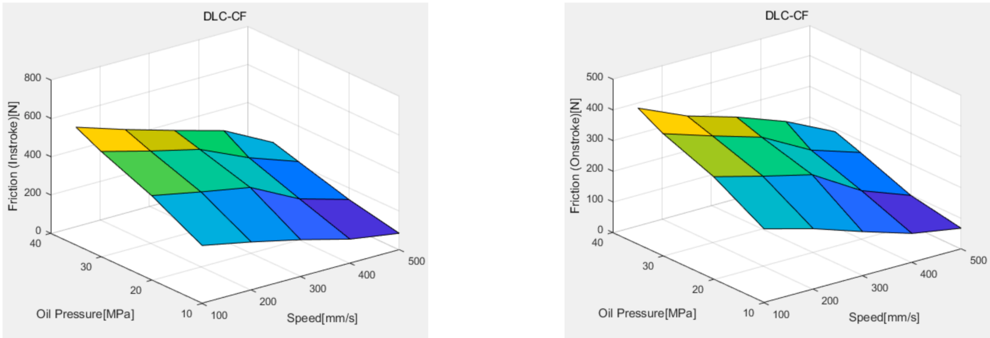


Figure 15. DLC-CF pressure-speed-friction three-dimensional diagram: (**a**) Instroke; (**b**) Outstroke.

3.1.3. Comparison of Friction between Piston Rods of Different Coating Materials

The experimental data of the frictional forces processed by the above two groups were taken, and the maximum and minimum frictional forces of the instroke and outstroke were compared, respectively. The comparison results are shown in Figure 16.

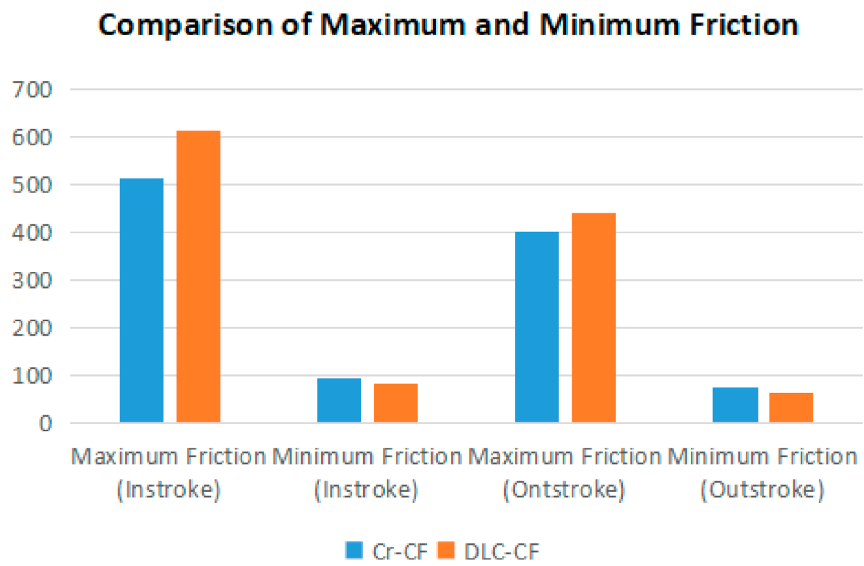


Figure 16. Comparison of contact friction between different materials coated piston rod.

It can be seen from Figure 16 that the maximum friction of the chrome-coated piston rod and the sealing ring at instroke is the smallest, and the chrome-coated piston rod has less friction than the DLC-plated piston rod, but the difference between the two is small. Therefore, in order to select a better coating material, the interface wear test of the reciprocating sealed bench test is also required.

3.2. Sealing Lip Interface Performance Analysis

3.2.1. The Surface Morphology of Sealing Lips

The Nexview three-dimensional white light interference surface topography instrument was used to determine the surface topography of the inner lip of the seal. The measurement results are shown in Figures 17–19.

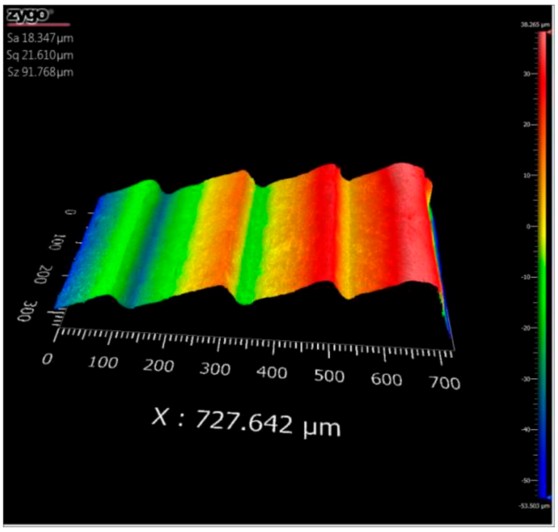
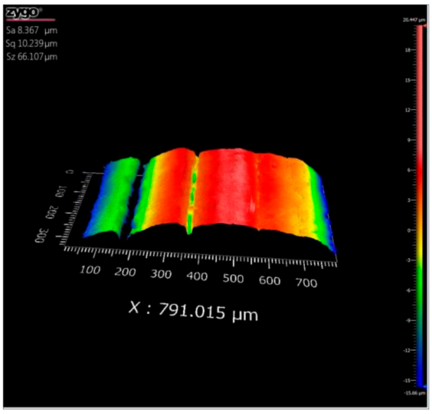
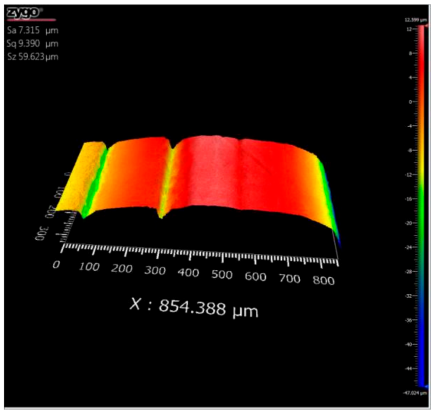


Figure 17. New seal lip.

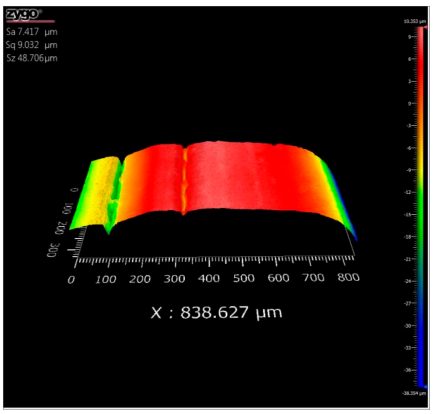


(**a**)



(**b**)

Figure 18. Seal lips contact with chrome-coated piston rod. (**a**) Cr-1; (**b**) Cr-2.



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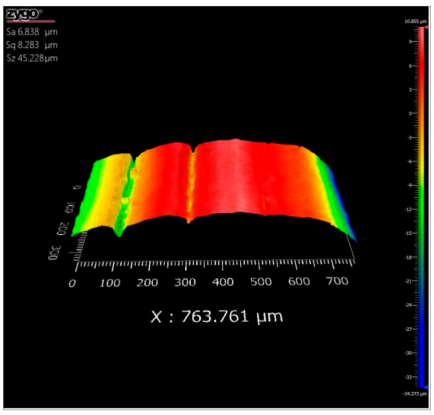


(**b**)

Figure 19. Seal lips contact with DLC-coated piston rod. (**a**) DLC-1; (**b**) DLC-2.

Figure 17 shows the measurement results of the inner lip of the new, unused seal ring. The turning marks of the seal ring can be clearly seen and arranged neatly.

Figures 18 and 19 are, respectively, measurement results of the inner ring lip of the sealing ring, which are in contact with the chrome-coated piston rod and the DLC-coated piston rod. It can be seen from the figures that the turning marks processed by the sealing ring are squeezed and the contour of the turning marks is blurred. The measurement results of the five samples are listed in Table 4, the results include arithmetic mean height (Sa), root mean square height (Sq) and maximum height (Sq).

Table 4. Measurement results (μm).

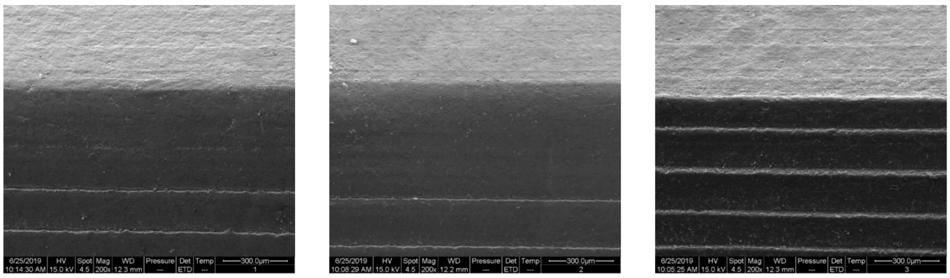
Samples		Sa	Sq	Sz
New		18.347	21.610	91.968
Cr	Cr-1	8.367	10.239	66.107
	Cr-2	7.417	9.032	48.706
DLC	DLC-1	7.315	9.390	59.623
	DLC-2	6.838	8.283	45.228

It can be seen from the three-dimensional diagram and measurement results that after the sealing ring is pressed against the piston rod, although it rebounds, the rebound is less than the original position. The sealing ring, which is in contact with the plated DLC-coated, is more compacted than the lip of the sealing ring, which is in contact with the Cr-coated shaft, and the rebound is smaller.

3.2.2. Surface Wear of Seal Lips

The field emission environment scanning electron microscope was used to measure the surface wear of the inner lip of seals. The experimental results are as follows.

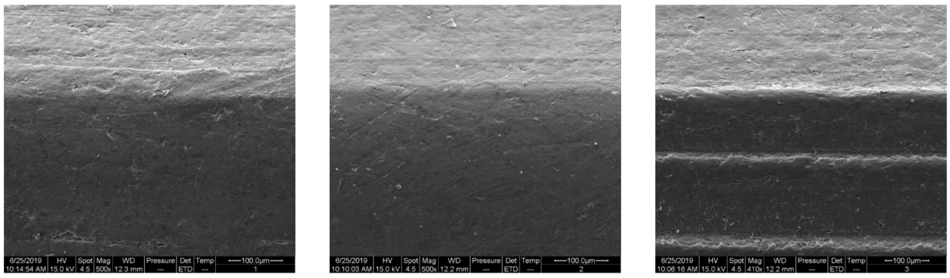
As shown in Figure 20, there are electron microscope experimental measurement results of magnification of 200 times. It can be seen from the figures that the new, unused sealing ring has neatly arranged turning marks, and the two seal ring test samples used in the reciprocating test bench experiment have no obvious turning marks after the seal lips are pressed after contact with the piston rod.



(**a**) (**b**) (**c**)

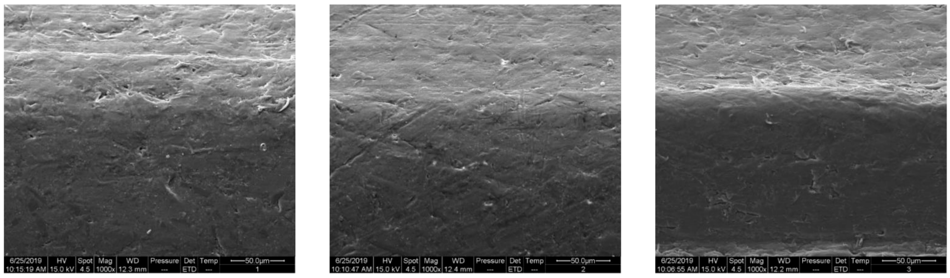
Figure 20. Seal lip magnify 200 times. (**a**) Cr-1; (**b**) DLC-1; (**c**) New.

Figures 21 and 22 show the results of electron microscopy experiments obtained by magnifying 500 times and magnifying 1000 times, respectively. It can be seen from the figures that the two seal ring experimental samples used in the reciprocating test bench experiment are worn after the piston rod is in contact with the piston rod, and the seal ring lip contact with the Cr-plated piston rod is shallow, the seal ring that is in contact with the DLC piston rod is worn deeper. The wear marks are in the same direction and are streamlined, indicating that there is abrasive grain between the seal ring and the movement of the piston rod. The abrasive grains cause the surface of the lip of the seal ring to wear and form wear marks. Since the sealing ring PTFE material is softer than the piston rod coating material, the abrasive particles are off the piston rod coating material.



(**a**) (**b**) (**c**)

Figure 21. Sample 1-1 seal lip magnify 500 times. (**a**) Cr-1; (**b**) DLC-1; (**c**) New.



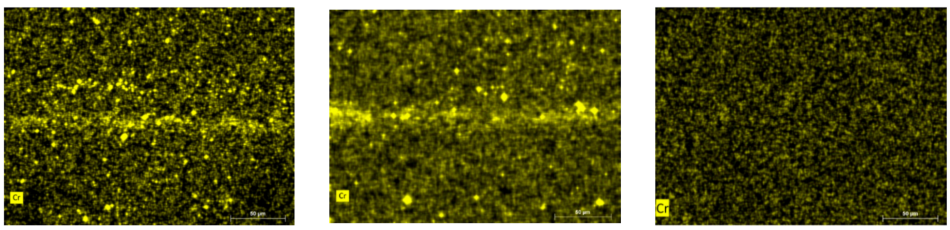
(**a**) (**b**) (**c**)

Figure 22. Sample 3 seal lip magnify 1000 times. (**a**) Cr-1; (**b**) DLC-1; (**c**) New.

3.2.3. Wear Surface Elements of Sealing Lips

The surface of the five samples was plated with a Pt film, and the surface elements of the wear lip on the inside of the seal were measured by a cold field emission high-resolution scanning electron microscope., Select the magnification of 500 times for the experiments, the measurement elements were Cr, C, and Fe, and the experimental results were as follows.

Figure 23 shows the Cr element measurement results for the three samples with the Cr-coated contact seal and the new, unused seal lip. In the figure, the bright yellow spot is where the Cr element exists, and the Cr element mainly exists between the two seal marks of the sealing lip. It can be seen from the comparison of the 3 figures that the lip of the seal ring, which is in contact with the Cr-coated shaft, has obvious Cr element residue, and the Cr element remains at the turning dent. It indicates that the surface material of the Cr-coated shaft is worn and material transfer occurs.



(**a**) (**b**) (**c**)

Figure 23. Experimental results of measuring Cr elements. (**a**) Cr-1; (**b**) Cr-2; (**c**) New.

Figure 24 shows the C element measurement results for two samples of the DLC-coated piston rod contact seal and the new, unused seal. The bright green dots in the figure are where the C element exists. It can be seen from the comparison of Figure 24a,b that the content of the element C of the seal ring, which is in contact with the plated DLC-coated piston rod increases, however, the amount of Cr element added to the seal of the Cr-coated piston rod is less than that of Figure 23a,b. As can be seen from Figures 23 and 24, the material of coating materials of the two coated piston rods has undergone material transfer, and the material of the Cr-coated film has a large amount of transfer and large wear.

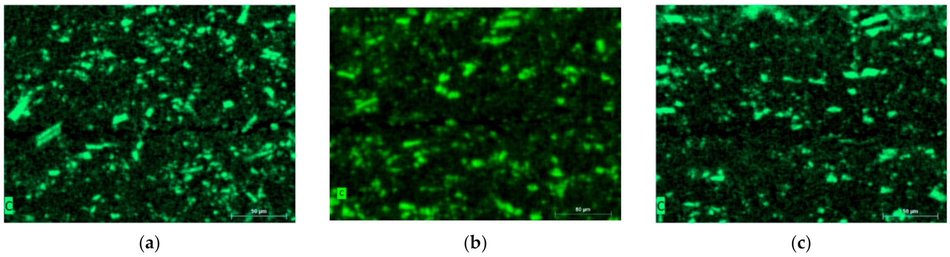


Figure 24. Experimental results of measuring C elements. (**a**) DLC-1; (**b**) DLC-2; (**c**) New.

Figure 25 shows the Fe element measurement results for five samples at the same time. The bright orange spot is the presence of Fe element, and the Fe element is mainly between the two seal marks of the sealing lip. It can be seen from the comparison of Figure 25, that there is Fe element residue in the lip of the sealing ring, which is in contact with the Cr-coated piston rod and in contact with the DLC-coated piston rod, and the Fe element remains in the turning dent. It shows that the coating material on the surface of the Cr-coated piston rod and the DLC-coated rod is worn, and the Fe element in the stainless steel piston rod is transferred.

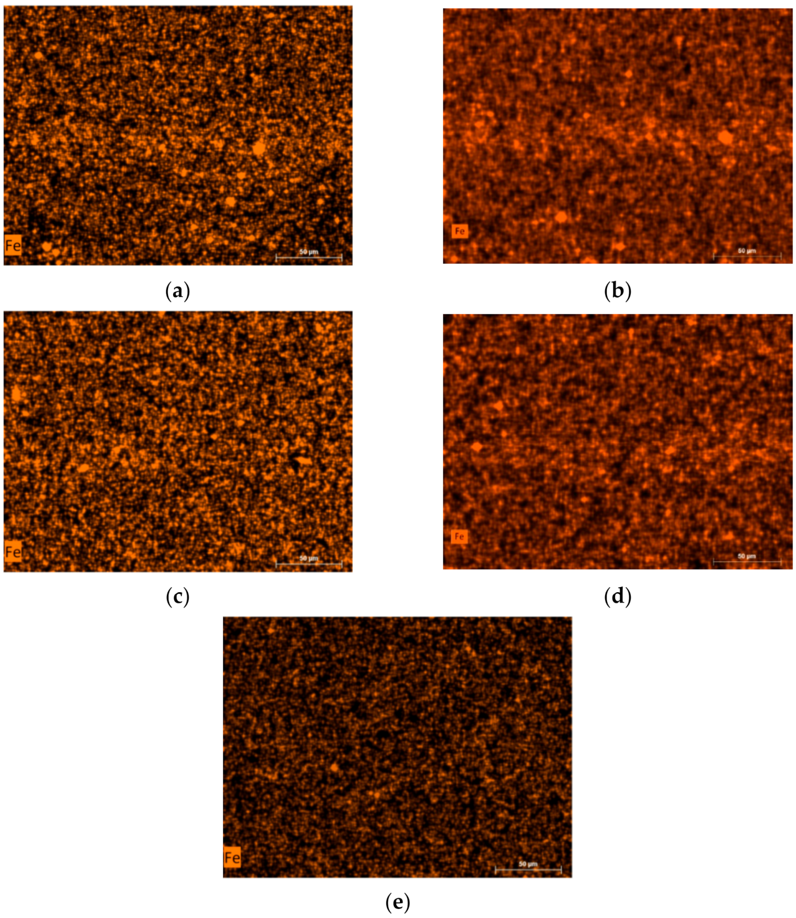


Figure 25. Experimental results of measuring Fe elements. (**a**) Cr-1; (**b**) Cr-2; (**c**) DLC-1; (**d**) DLC-2; (**e**) New.

It can be seen from this experiment that although the sealing ring PTFE material is softer than the two coating materials, element transfer occurs with the dual material after the contact movement. The amount of Fe element in the sealing ring, which is in contact with the Cr-coated piston rod, is larger than the sealing ring, which is in contact with the DLC-coated piston rod, indicating that the Cr-plated film is worn more.

3.3. Sealing Ring and Piston Rod Processing Recommendations

According to the test of the sealing surface of the sealing lip, it is known that the transfer of the dual material elements of the sealing ring is concentrated between the turning marks of the lip of the sealing ring. Therefore, the height difference of the turning edge of the sealing ring has a great influence on the friction and wear of the piston rod, and the height difference between the two turning points can be reduced by increasing the precision of the turning machine.

According to the test of surface wear and wear surface elements of the sealing lip, the DLC coating material is better than the Cr coating material, but the abrasive particles are peeled off due to the falling off of the coating material, which causes the seal lip to wear and form a wear scar. Therefore, the coating material of the piston rod is reinforced, such as plating a chrome film before plating the DLC film and then plating the DLC film, thereby preventing the coating material from falling off and damaging the sealing ring.

4. Conclusions

In this chapter, through the surface morphology of the sealing lip, surface wear, and surface element determination experiments, the following conclusions are obtained:

(1) DLC (diamond-like) material is hard. In the white light interference experiment, the lip of the seal ring which is in contact with the DLC-coated piston rod is obviously worn, and the wear amount is large. In the cold field emission electron microscopy experiment, the element content of the sealing ring contact area C in contact with the DLC-coated piston rod is increased. The Cr material is soft. In the white light interference experiment, the lip of the seal ring which is in contact with the Cr-coated piston rod is not obvious, and the wear amount is small. In the cold field electron microscopy experiment, the content of Cr in the contact area of the sealing ring in contact with the Cr-plated piston rod is significantly increased. In summary, DLC-coated materials are better.

(2) Since the coating layer of the piston rod is detached, abrasive grains are generated, and the abrasive grains cause the seal ring to be worn and form a wear scar. The coating of the Cr-coated piston rod and the DLC-coated rod have different degrees of damage, and the material transfer of the stainless steel piston rod metal causes an increase in the Fe element content of the two used seals. Although the sealing ring PTFE material is softer than the two coating materials, element transfer occurs with the dual material after the contact motion.

(3) The friction and wear of the piston rod on the piston rod can be reduced by increasing the precision of the turning machine and reducing the height difference between the two turning marks. At the same time, the coating material should be reinforced before the piston rod is coated to prevent the coating material from falling off and destroying the sealing ring.

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References

1. Craggs, A. The transient response of a couple plate-acoustic system using plate and acoustic finite elements. *J. Sound Vib.* **1971**, *4*, 509–528. [CrossRef]
2. Suzuki, S. Boundary element analysis of cavity noise problems with complicated boundary. *J. Sound Vib.* **1989**, *130*, 147–153. [CrossRef]
3. Zhang, M.T.; Suo, S.F.; Jiang, Y.; Meng, G.Y. Experimental Measurement Method for Contact Stress of Elastic Metal Sealing. *Metals* **2018**, *8*, 942. [CrossRef]
4. Zhang, M.; Suo, S.; Guo, F.; Jia, X.; Meng, G. Research of Forward Design Method of Contact Dynamic Seal. *IOP Conf. Ser.: Mater. Sci. Eng.* **2018**, *408*, 012012.
5. Zhang, M.T.; Shi, S.W.; Suo, D.F.; Meng, G. Experimental Study of Friction and Wear Interface Performance of Reciprocating Seal based on Sterling Seal. *Chin. Hydraul. Pneum.* **2019**, *11*, 99–104.
6. Nikas, G.K.; Sayles, R.S. Nonlinear Elasticity of Rectangular Elastomeric Seals and its Effect on Elastohydrodynamic Numerical Analysis. *J. Tribol. Int.* **2004**, *37*, 651–660. [CrossRef]
7. Thatte, A.; Salant, R.F. Transient EHL Analysis of an Elastomeric Hydraulic Seal. *J. Tribol. Int.* **2009**, *42*, 1424–1432. [CrossRef]
8. Weber, D.; Hass, W. Wear Behavior of PTFE Lip Seals with Different Sealing Edge Designs, Experiments and Simulation. *J. Seal. Technol.* **2007**, *2*, 7–12. [CrossRef]
9. Nikas, G.K. Eighty years of research on hydraulic reciprocating seals: Review of tribological studies and related topics since the 1930s. *Proc. Inst. Mech. Eng Part J J. Eng. Tribol.* **2010**, *224*, 1–23. [CrossRef]
10. Crudu, M.; Fatu, A.; Cananau, S.; Hajjam, M.; Pascu, A.; Cristescu, C. A numerical and experimental friction analysis of reciprocating hydraulic 'U' rod seals. *Proc. Inst. Mech. Eng Part J J. Eng. Tribol.* **2012**, *226*, 785–794. [CrossRef]
11. Wu, Q.; Suo, S.F.; Liu, X.F.; Huang, W.F.; Wang, Y.M. Static Sealing and Pseudo-sealing Characteristics of Nitrile Rubber O-ring. *Lubr. Eng.* **2012**, *11*, 21.
12. Yang, B.; Salant, R.F. Elastohydrodynamic lubrication simulation of O-ring and U-cup hydraulic seals. *Proc. Inst. Mech. Eng Part J: J. Eng. Tribol.* **2011**, *225*, 603–610. [CrossRef]
13. Fatu, A.; Hajjam, M. Numerical modelling of hydraulic seals by inverse lubrication theory. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2011**, *225*, 1159–1173. [CrossRef]
14. Bhaumik, S.; Kumar, S.R.; Kumaraswamy, A. Experimental Investigation and FE Modelling of Contact Mechanics Phenomenon in Reciprocating Hydraulic U-Seals for Defence Applications. *Appl. Mech. Mater.* **2014**, *592–594*, 1950–1954. [CrossRef]
15. Huang, L. *Simulation Research on Performance of Reciprocating Seal Used in Stamping Equipment*; Tsinghua University: Beijing, China, 2015.
16. Huang, L.; Jia, X.H.; Guo, F. Optimization Design of Y-Sealing Ring Based on Finite Element Analysis. *Lubr. Eng.* **2014**, *39*, 83–88.
17. Jia, X.H.; Guo, F.; Huang, L.; Wang, L.; Gao, Z.; Wang, Y. Effects of the radial force on the static contact properties and sealing performance of a radial lip seal. *Sci. China Technol. Sci.* **2014**, *57*, 1175–1182. [CrossRef]
18. Dilixiati, A. *Reliability Modeling and Experimental Research of Pneumatic Y Seal*; Tsinghua University: Beijing, China, 2015.
19. Dilixiati, A.; Suo, S.F.; Huang, L. Finite Element Analysis on Reliability and Sensitivity of Y-Seal. *Lubr. Eng.* **2015**, *4*, 5–10.
20. Li, Q.; Wang, D.; Zhang, W. Static Sealing Performance and Reliability Finite Element Analysis for Air Hydraulic Actuator O-ring. *J. Chin. Hydraul. Pneum.* **2018**, *4*, 69–73.
21. Guo, F. Research on Dynamic Evolution Rule of Rotary Lip Seals' Performance Based on Aging and Wear. Ph.D. Thesis, Tsinghua University, Beijing, China, 2014.
22. Guo, F.; Jia, X.H.; Huang, L.; Wang, Y.M. A Mixed Lubrication Theoretical Model and Experimental Verification of Rotary Lip Seals. *J. Mech. Eng.* **2014**, *50*, 137–144. [CrossRef]
23. Chang, K. Wear Simulation Method of O-ring Based on ANSYS. *J. Chin. Hydraul. Pneum.* **2018**, *2*, 98–103.
24. Ye, S.J. The Friction and wear Properties of The PTFE composites for Seal. In Proceedings of the National Youth Tribology and Surface Engineering Conference, Beijing, China, 22–24 May 2011.
25. Zheng, X.P.; Shen, X.M.; Li, G.; Peng, X.D. Friction and Wear Characteristics of Acrylonitrile-butadiene Rubber Under Hard Particles Condition. *J. Mater. Eng.* **2015**, *43*, 79.
26. Wu, C.G. Research on Maining Sealing Performance of High Pressure Aircraft Actuator. Master's Thesis, Tsinghua University, Beijing, China, 2016.
27. Zhang, F.Y.; Zhao, L.; Li, J.B. Effect of Surface Roughness on Dynamic Sealing Performance of Rectangular Elastomeric Seals. *Lubr. Eng.* **2015**, *40*, 30–33.
28. Zhu, J. Research of the Hydrodynamic Sealing Mechanism and Experiment of Variable Cross Section Sealing Ring. Ph.D. Thesis, Northeast Petroleum University, Daqing, China, 2017.
29. Yang, F. Research on Friction and Wear Performance of NBR as the Stator of Progressing Cavity Pump. Ph.D. Thesis, Shenyang University of Technology, Shenyang, China, 2014.
30. Li, X.; Suo, S.; Guo, F.; Wu, C.; Jia, X. A study of reciprocating seals with a new mixed-lubrication model based on inverse lubrication theory. *Lubr. Sci.* **2018**, *30*, 126–136. [CrossRef]
31. Wen, S.Z.; Huang, P. *Principles of Tribology*; Tsinghua University Press: Beijing, China, 2018.