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APPLICATIONS OF TEXTURED SURFACES TO HYDRAULIC SYSTEM COMPONENTS: A REVIEW

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Abstract: *This paper presents an analysis of how micro-textures created on the surfaces of various hydraulic components influence friction, wear, lubrication and energy efficiency. The first part describes the main causes of failure of hydraulic components, such as abrasion, corrosion, material fatigue and wear of sealing elements. Subsequently, recent results from the specialized literature on the performance of textured components are synthesized, including experimental studies and numerical models that highlight the role of micro-cavities in capturing wear particles, maintaining the lubricating film and reducing the friction coefficient.*

Keywords: *Hydraulic applications, surface texturing, tribological performance, abrasive wear, friction, stress corrosion cracking*

1. Introduction

Hydraulic systems are used to transfer energy by converting mechanical energy into hydraulic energy and then back into mechanical energy. The main reason for converting mechanical energy into fluid energy is the convenience of easily transferring it. The transmission and control of power by means of pressurized fluid is widely used in all branches of industry and mobile equipment [1].

Hydraulic systems are made up of several components, as follows: hydraulic cylinder, piston and fluid flow pipes, sealing systems and guide elements, hydraulic pump, pressure regulator, control valve, filters and storage tank [2], [3].

Hydraulic cylinders are actuator components that convert hydraulic energy into mechanical energy and generate linear motion through pressure exerted on the surface of the moving piston [4].

The piston is the component of the hydraulic cylinder composed of piston body, rod, connectors and other components. The connection between the piston and the piston rod is made depending on the working pressure, installation and operating conditions of the system. The piston has the role of separating two working chambers in a cylinder and preventing the flow of working fluid between the two chambers [5, 6].

The guide elements ensure the centring of the piston in the cylinder. They transmit lateral forces and absorb radial loads [7].

Seals prevent the flow of hydraulic fluid both between the cylinder chambers and to the outside and prevent the transfer of oil contamination from the outside to the inside of the cylinder but also contribute to increasing the service life of components. Seals are of great importance for the efficiency of hydraulic systems, because they prevent lubricant losses. If oil leaks occur, then pressure losses also occur in the hydraulic system and thus, it loses its efficiency [4, 7, 8, 9].

The hydraulic pump is the component of the system that converts mechanical energy into hydraulic energy. It is responsible for creating hydraulic pressure by pumping fluid from the reservoir into the system [10].

A directional control valve is a component of a hydraulic system used to control the distribution of power by directing hydraulic fluid, allowing it to flow in one direction only. This valve is used to start, stop, and change the direction of the flow of lubricant [2].

The pressure regulator/pressure control valve is an essential component of a hydraulic system, as it protects the hydraulic components from excessive pressure and helps the system to function optimally. The main role of this component is to limit the pressure in the system within a specified range, usually the pressure regulator is closed and opens only when the pressure in the system exceeds the maximum preset value, directing the flow of lubricant from the pump back to the reservoir [2, 10].

Filters are components of a hydraulic system that purify hydraulic fluid, being the most effective method against contamination [11].

2. Failures of hydraulic system components

The most common causes of failure of hydraulic components are abrasive wear, material fatigue and friction, but the most significant cause of damage to cylinders, pistons and piston rods can be corrosion. To prevent its occurrence, it is necessary to use corrosion-resistant materials or apply anti-corrosion coatings to the surface of these components. Faults in hydraulic cylinders can occur both from the manufacturing process and from the operating mode, since these components are used under high pressure conditions, in this case, material fatigue, corrosion and even fatigue cracking most often occur. Damaged parts of hydraulic cylinders are those that show cracks, cavities, deformations, seizing and can be corroded to varying degrees [7, 12, 13].

Piston rods are the elements that fail most often, as they are subject to high tensile and compressive stresses, but also to external factors such as temperature changes, precipitation, dust and dirt. In their work, Moreira D. et al. analysed the causes of failure of the piston rod of a hydraulic cylinder used to move a weir. The material used to make the piston rod was stainless steel. The results of the analysis showed that the crack (Fig. 1.) could have been caused by the low performance of the hydraulic component. This low performance could be due to improper heat treatment during the rod manufacturing process, which led to low material hardness, embrittlement at temperature, and stress corrosion cracking [14].

Fig. 1. Cracked surface of the piston rod, followed by component failure [14]

Sealing systems are important elements of hydraulic systems that are exposed to external factors, due to which failures such as: swelling, thermal degradation, deformation and wear can occur. Destruction of sealing systems leads to fluid leakage (loss of tightness) and even failure of the entire hydraulic system [7].

In the work of J. Bae and K.H. Chung [15] three situations of contact between seals and hydraulic cylinders were studied. For the three situations, a hydraulic seal made of a polyurethane elastomer was used as the material pair, and the counter material of the hydraulic cylinder was galvanized stainless steel with chromium. The lubricant used was ISO VG 46 under several conditions, one was a new lubricant, the second was worn for 1000 hours, and the third was the new lubricant in which 1 µm aluminium oxide particles were introduced to accelerate abrasive wear. The first situation was the study of three polyurethane rings obtained from an excavator after being used for 26, 11 and 10 months, during which they operated for 2989, 955 and 632 hours. The lubricant introduced was a new lubricant, but its change at a certain time interval could not be monitored. The hydraulic pressure at which it worked was between 0 and 22 MPa, with a sliding speed from 0 to several hundred mm/s, at a maximum stroke of the pistons of 850 mm in operation. Fig. 2. shows photographs of the polyurethane rings after operation.

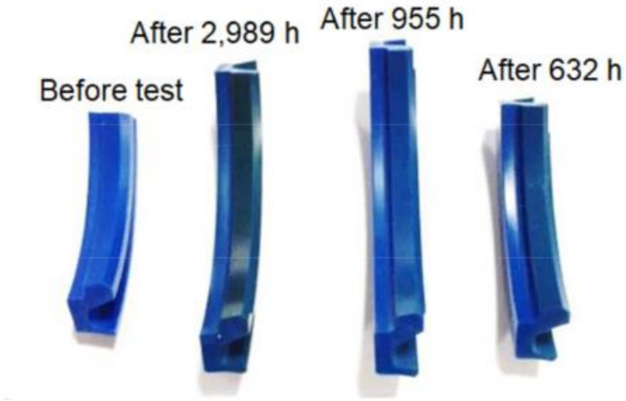

Fig. 2. O-rings before testing, after 2989, 955 and 632 hours [15]

The second set of tests was performed on a hydraulic seal test stand shown in Fig. 3. The hydraulic pressure during one cycle varied from 0 to 22 MPa. The maximum sliding speed was 180 mm/s at the mid-section of the hydraulic cylinder when the hydraulic pressure was 22 MPa. The temperature was set to 100°C. These conditions are like the harsh conditions experienced in the field. The test stroke was set to 200 mm. Four polyurethane rings were tested with a new lubricant, and the test times were 694, 726, 909, and 941 hours, which corresponded to sliding distances of 250, 261, 327, and 339 km, respectively.

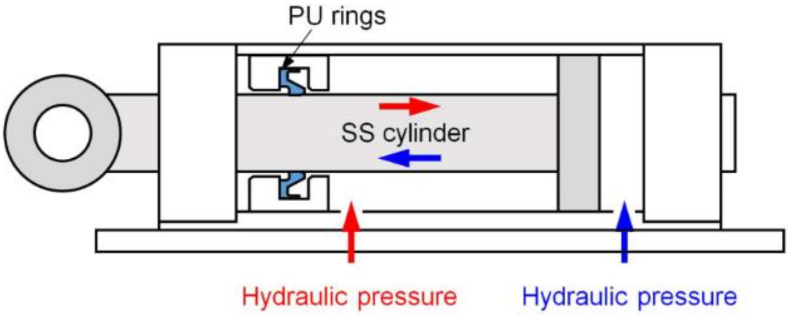

Fig. 3. Hydraulic seal tester [15]

Fig. 4. shows photographs of the specimens obtained from the polyurethane rings after 694, 726, 909 and 941 hours of testing. As can be seen from the images, all the specimens proved to be significantly discolored after testing, the causes being due to the repetitive translational motion, high pressure and high temperatures.

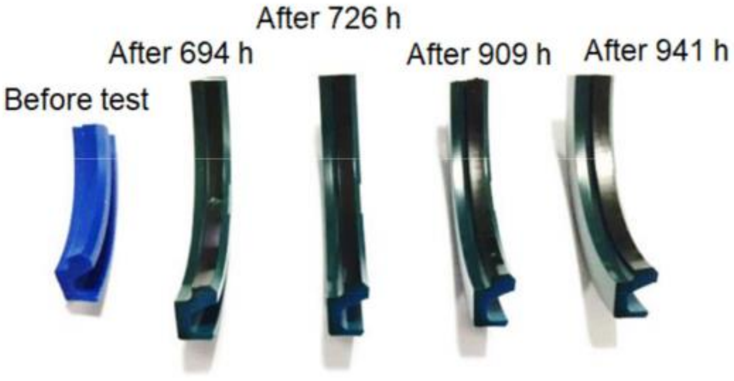

Fig. 4. Specimens after 694, 726, 909 and 941 hours of testing [15]

The third set of tests was performed using a tribometer exemplified in Fig. 5. Given that the lubrication state of a ring can vary from boundary lubrication to mixed lubrication, it is considered that the normal force and sliding speed can change the lubrication states during the test. The wear characteristics can be influenced by the interaction of particles and viscoelastic behavior under mixed or elasto-hydrodynamic lubrication conditions. The normal force was 200 N, corresponding to a contact pressure of approximately 10 MPa. This pressure was comparable to the average hydraulic pressure applied to the polyurethane rings during operation in service and during the test on the hydraulic seal tester.

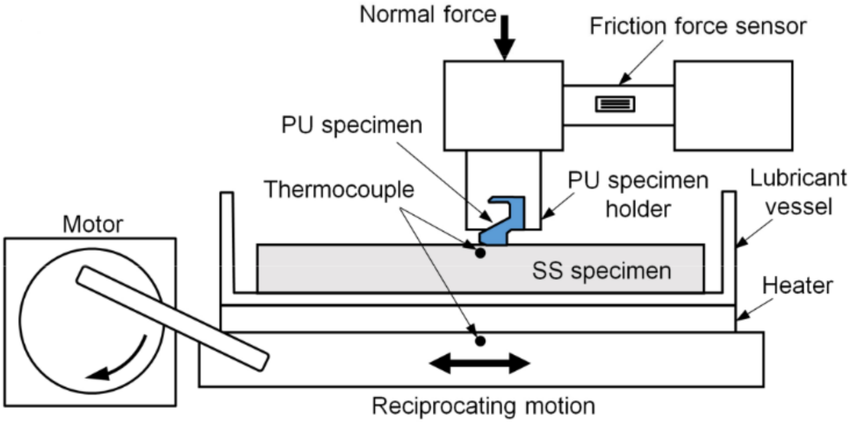

Fig. 5. Tribometer used for pin-on-disk tests [15]

Different from the polyurethane specimens obtained in the first two tests, in the case of the pin-on-plate tests, no significant discoloration was observed, probably due to the shorter testing time. The microscopic images of the sealing surfaces of the specimens for the tribometer tests, using three different lubricants, are presented in Fig. 6. The formation of scratches and grooves in the sliding direction can be clearly observed on all sealing surfaces, as seen in the high magnification images in the figure, indicating that the main wear mechanism observed in the field was reproduced using the pin-on-plate tests. In the case of the polyurethane specimens tested with lubricant B, relatively large scratches were observed on the sealing surface. The formation of scratches on the sealing surface was highest for the specimens tested with lubricant C. The particles in lubricant B were probably generated by the hydraulic system or the environment; therefore, they were softer than alumina. In addition, the number of alumina particles in lubricant C was higher than the number of particles in lubricant B.

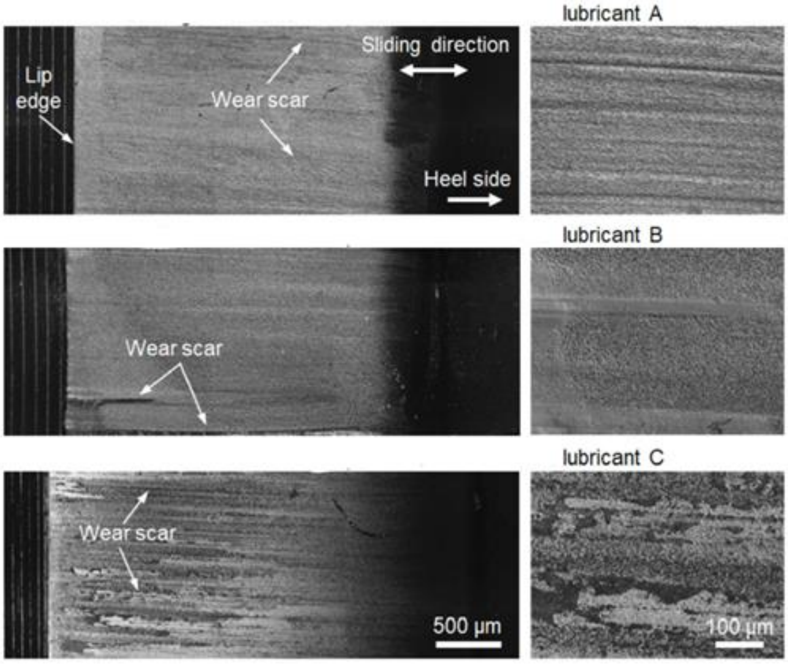

Fig. 6. Microscope images for tests performed with a tribometer [15]

The results showed that wear is mainly caused by abrasion, influenced by pressure, temperature, and lubricant contamination. Scratches, grooves, and plastic deformation were observed on the sealing surfaces under the microscope. Contaminated lubricant caused the most wear and increased the friction coefficient.

3. Applications of textured surfaces to hydraulic system components

Surface texturing consists of modifying the surface to create a micro-cavity composed of uniformly distributed asperities with a controlled geometry. Typically, these micro-cavities are created to improve the tribological properties of the systems. The situations for which micro-cavities are created are quite varied, such as dry friction sliding, hydrodynamic lubrication, elasto-hydrodynamic lubrication or even mixed lubrication [16, 17].
In recent years, research has been carried out on textured surfaces with micro-cavities of different sizes and geometries, made on hydraulic components, regarding tribological applications in the field of hydraulic installations.

A recent study [18] was conducted to improve the tribological performance of two materials found in the sealing area of hydraulic cylinders, polytetrafluoroethylene PTFE and 40# steel (AISI 1040), under fully lubricated conditions, using laser texturing technology to create micro-cavities on the surface of the steel discs. In this article, the authors aimed to optimize the parameters of the textured surface through repeated wear tests to reduce the coefficient of friction and wear between the two surfaces using anti-wear hydraulic fluid for fully lubricated components. The 40# steel discs were made with a diameter of 63 mm and a thickness of 5 mm, the material having a surface hardness of HB114, and their texturing was performed with laser technology (LST). It was necessary to make a hole with a diameter of 10 mm and an eccentricity of 7 mm to prevent the automatic rotation of the discs during the wear tests (Fig. 7. a) and b). The upper surfaces of the discs were polished with silicon carbide paper, and subsequently the surface roughness was measured using a profilometer, resulting in a surface roughness of approximately 0.8 μm. The rings were made of polytetrafluoroethylene (Fig. 7. a) and d) with an inner diameter of 35 mm, an outer diameter of 47 mm and a thickness of 15 mm. Also, in the case of the rings, it was necessary to polish the inner surface, resulting in a surface roughness of 1.1 μm. The texturing on the contact surface of the steel discs was performed with a fiber optic laser, for different diameters (200, 250 and 300 μm) and depths (5, 15 and 25 μm) of micro-cavities distributed uniformly around the circumference of the disc at an angle of 2.5° (Fig. 7. e). Before the texturing process the steel discs were cleaned with ultrasound, and after the texturing process the surface had to be repolished.

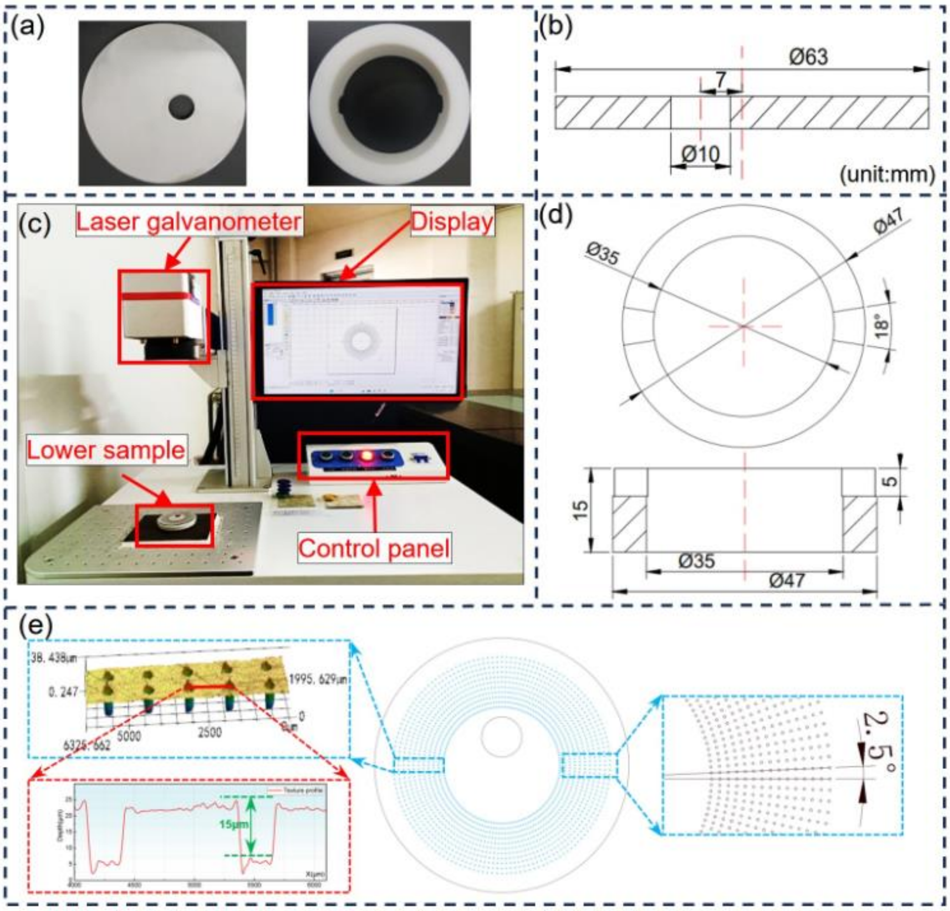

Fig. 7. Steel and PTFE components and the Laser used for surface texturing [18]

To perform tribological tests and study the sliding friction behavior of steel discs and PTFE rings, a vertical tribometer with a pin-on-disk configuration was used, shown in Fig. 8.: 1− upper device; 2− upper sample (PTFE ring); 3− lower sample (40# steel disc); 4− oil deflector; 5− lower device; 6− loading flange. Considering the operating parameters under normal working conditions applied to hydraulic cylinders, such as hydraulic system pressure less than or equal to 25 MPa and seal movement speed less than or equal to 3 m/s, the test parameters on the stand were chosen as: vertical external load of 1000 N, rotation speed of 200 rpm and test time of 2400 s, resulting in a sliding distance of 1 km. Before testing, a quantity of 25 ml of hydraulic lubricant was added to the lower device of the tribometer to completely submerge the disc. To obtain realistic results and minimize errors, each test was repeated three times, and the studied components were polished after each test.

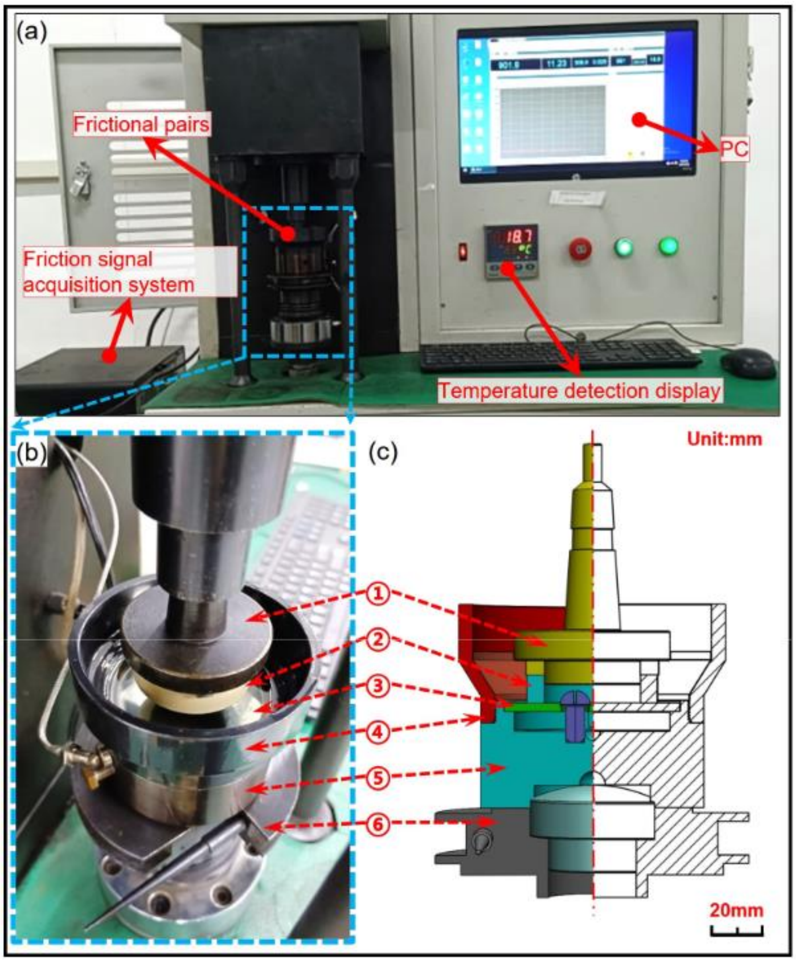

Fig. 8. Test stand - vertical tribometer [18]

The tests yielded results regarding the friction coefficient, which was significantly reduced due to the existence of micro-cavities on the surface of the discs, this result being important for improving the dynamic performance and lifespan of hydraulic cylinders. The wear losses of PTFE rings and 40# steel discs decreased by 91.8% and 30.3%, respectively, indicating that the micro-cavity parameters significantly increase wear resistance. It was concluded that this research and the results obtained are optimal for improving the tribological performance of seals, which can be used in hydraulic cylinders, and the surface texturing contributed to the capture of wear particles, preventing excessive abrasion and retaining lubricants, thus acting as small oil reservoirs and creating a hydrodynamic micro-bearing effect.

Another research on improving tribological conditions in hydraulic components that have textured surfaces is [19] where M. Gadari and M. Hajjam, analyze the effect of using a grooved rod on the friction force in a U-cup hydraulic seal, taking into account the roughness of the seal edge. U-cup rod seals (Fig. 9.) are often used in hydraulic systems because they operate under severe conditions of high temperatures and pressures and must prevent leakage from the system and the ingress of dirt from outside.

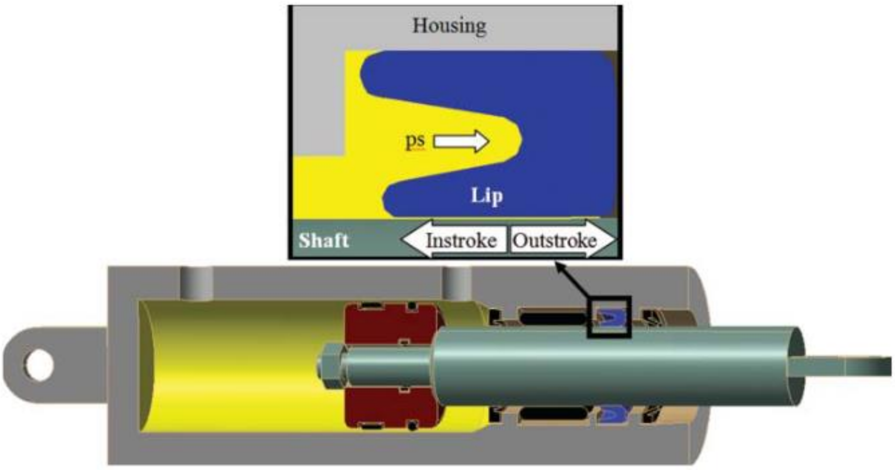

Fig. 9. Hydraulic cylinder with U-type rod seal [19]

Research has been carried out that analyzed the influence of surface roughness and different lubrication models, so starting from these, the authors of this article have developed a one-dimensional elasto-hydro-dynamic model to analyze the tribological behavior of seals. This model aims to analyze the interaction between the lubricant and the elastic deformation of the seal edge, taking into consideration the roughness of the rod and the seal edge and comparing the results obtained with the inverse hydrodynamic lubrication (IHL) model and with existing experimental data. Fig. 10. highlights the piston rod seal and the sealing area, for which it is desired to determine the hydrodynamic pressure, the distribution of the lubricant film thickness and the friction over the contact width between the two components, the structural analysis of the model where it was necessary to simulate the seal assembly and calculate the static contact pressure distribution.

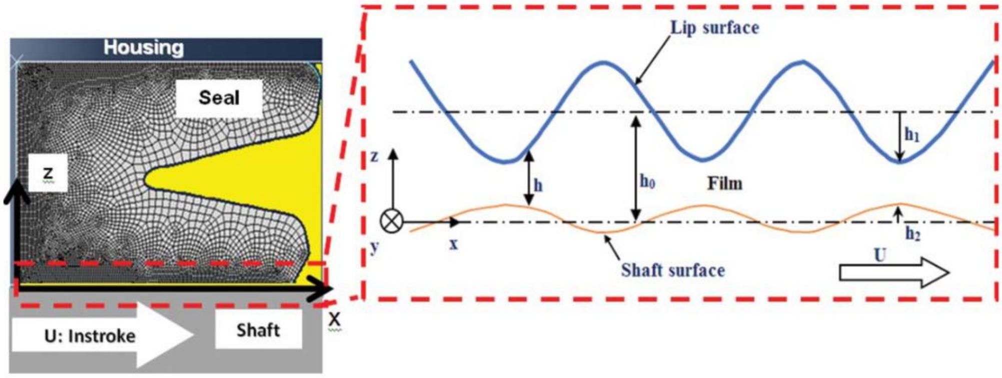

Fig. 10. U-type seal mounted on the stem [19]

Three types of grooves on the rod surface were tested and compared, shown in Fig. 11., SH#1 with rectangular grooves, SH#2 with asymmetrical grooves inclined towards the fluid pressure side and SH#3 with asymmetrical grooves inclined towards the air pressure side. It was found from the tests that the SH#3 surface with asymmetrical profile contributes to complete lubrication and significantly reduces the friction force compared to other surfaces.

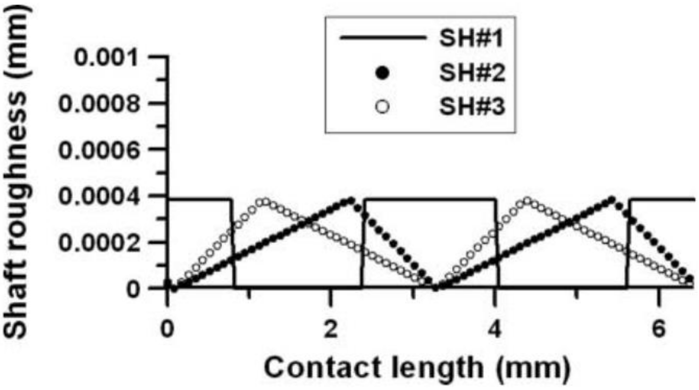

Fig. 11. Profile of the rod grooves [19]

The results of the obtained model were compared with experiments carried out by other researchers, and the difference between the numerical simulations and the experimental data was approximately 7%, thus confirming the accuracy of the model compared to the results obtained with the inverse hydrodynamic lubrication (IHL) model. It was observed that the roughness of the rod significantly influences the friction force and the power loss due to the hydrodynamic pressure generated by the rod's roughness, which increases the thickness of the lubricant film, therefore the roughness must be considered to obtain realistic results. At the same time, it was found that a greater depth of the grooves reduces the friction and power losses in the system, while a higher density can lead to increased friction.

Swash plate axial piston pumps are frequently used in hydraulic installations, as they have a simple and compact construction. These pumps have three lubrication interfaces: the piston-cylinder interface, the swash plate interface and the cylinder block-valve interface. Thus, starting from these aspects, the authors of the paper [20] investigate how the textured surface of the valve plate influences the tribological performance of the interface between the cylinder block and the valve plate in an axial piston pump. This research includes both the development of a mathematical model and numerical and experimental simulations to analyze the effect of texturing on the lubricant film and fluid leakage. The cylinder block has relative rotational movement on the valve plate, having the task of adjusting its position to take on the external load by changing the pressure area in the lubricant film. The structure of the cylinder block valve interface is shown in Fig. 12., consisting of the cylinder block, piston, valve plate and lubricant film.

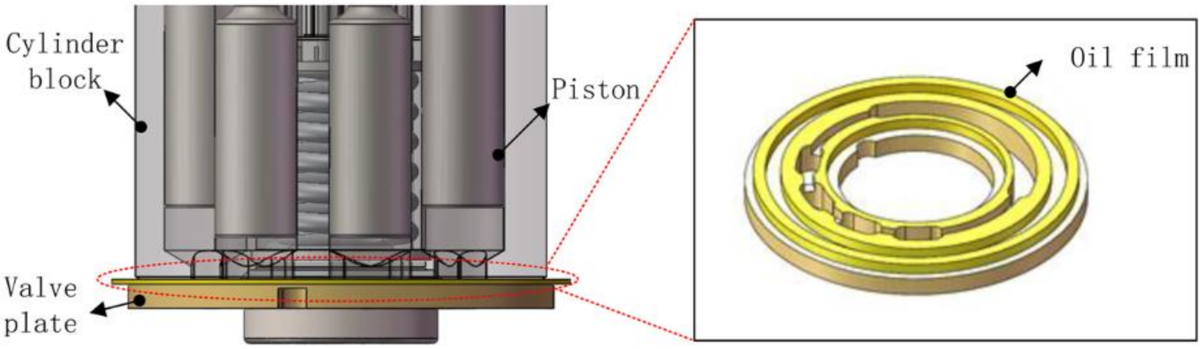

Fig. 12. Interface structure between cylinder block and valve plate [20]

In this study, the surface exploration was carried out by regularly arranging microcavities on the surface of the valve plate, as shown in Fig. 13. The parameter values used for this study are cylinder block radius of 45 mm, valve plate diameter of 88 mm, microcavity depth of 30 μm, and microcavity radius of 50, 100, 150, and 200 μm Fig. 14. To investigate the influence of microcavities on the lubrication mode, the authors considered equations for lubricant film thickness, pressure distribution, and flow leakage, and developed a mathematical model based on them.

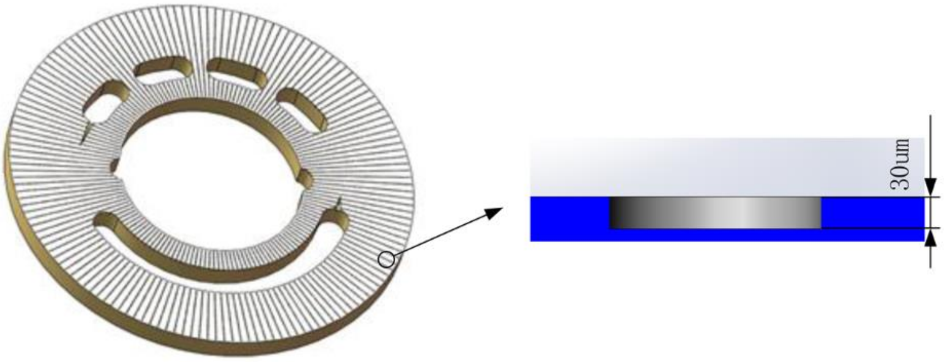

Fig. 13. Valve plate model with textured surface [20]

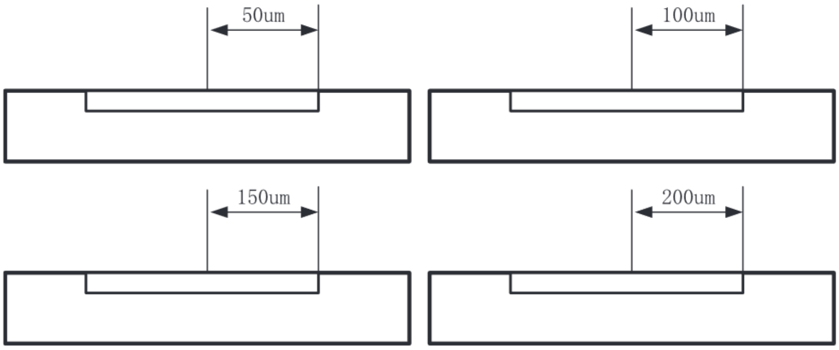

Fig. 14. Micro-cavity radii [20]

The numerical simulation part was performed for all four dimensions of the micro-cavities at a pump rotation speed of 2000 rpm, using calculation methods for pressure distribution and leakage flow. The simulation results showed that the pressure distribution is influenced by the size of the micro-cavities and increases with it. It was observed that when the radius of the micro-cavities increased from 50 μm to 100 μm, the pressure increased fourfold. Another result obtained from the numerical simulation showed that the leakage flow of the lubricant is directly proportional to the size of the micro-cavities, and the thickness of the lubricant film was influenced by the position in the interface, having lower values in the suction zone and higher values in the discharge zone. Following simulations and their analysis, it was found that micro-cavities with the smallest radius (50 μm) reduce lubricant leakage and provide good lubrication, being the optimal texturing option for this application.

For the experimental part, a test stand was created (Fig. 15.) consisting of a pump set at 2000 rpm, a hydraulic motor, a coupling and a torque sensor for measuring friction resistance, sensors for measuring pressure, lubricant film thickness and leakage flow rate.

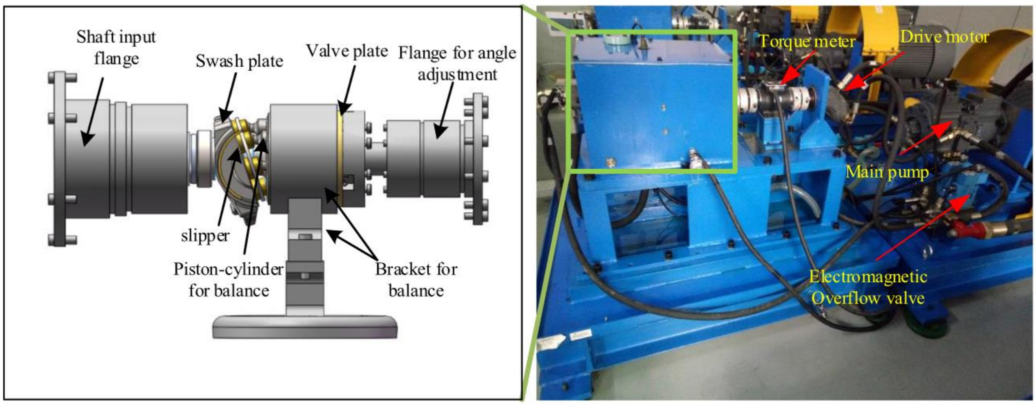

Fig. 15. Experimental test stand [20]

For testing the four micro-cavity sizes, the maximum applied pressure was between 6 and 14 MPa and a standard hydraulic oil was used. The experimental results were like simulation results, both for pressure and leakage flow. For example, the maximum pressure measured for the 100 μm micro-cavities was 9620 Pa, and in the case of leakage flow for the 50 μm texture size, the leakage was 0.0521 mm^3/s and for the 200 μm micro-cavities, the leakage flow was 0.7036 mm^3/s, which confirmed the increase in leakage flow with increasing texture size. Thus, it was concluded that texturing the valve plate significantly reduces lubricant leakage, the experimental results validating the simulation results, and the optimal texturing variant is that micro-cavities with a size of 50 μm, as it offers the best transmission efficiency, balances lubrication and reduces lubricant losses.

4. Conclusions

Hydraulic systems with textured component surfaces are part of a new and highly interesting field.
Surface texturing is a modern solution for creating tribological performance of components used in hydraulic systems.
Research in this field shows that surface texturing improves lubrication, reduces friction, and increases the service life of components and the entire system.
Studies have shown that the use of micro-textures on the surfaces of hydraulic components can significantly improve energy efficiency, lubrication performance, and system durability.

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