Mechanical properties of fluoroplastic seals of axial-piston pumps in relation to the operating conditions of a hydraulic drives

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Abstract. The article considers the issues associated with the elastic and plastic properties of fluoroplastic in the state of delivery and radiation hardened. The statement about the radiation hardening of fluoroplastic improves thermal deformation characteristics is substantiated. The results of kinetic microindentation are studied in comparison with the initial state in the temperature range of 80 - 400 0C. The effect of temperature on the ratio of the work of the elasticity and plasticity forces is analyzed. Particular attention is paid to the elastic properties of fluoroplastic. The assumption is substantiated that it is possible to improve the elastic properties of fluoroplastic by radiation treatment at elevated temperatures, which are typical for high-speed axial piston pumps. On the basis of the study, it was found that the use of radiation hardening treatment of fluoroplastic is promising for increasing the durability of movable seal rings.

1 Introduction

The failure of axial piston pumps is mainly due to the wear of the friction surfaces. The wear resistance of the piston-cylinder pair is critical to the performance and reliability of an axial piston pump. The wear of the friction surfaces leads to seal failure and leakage of the working fluid. An effective measure to reduce the harmful effects of wear on friction surfaces is the installation of sealing rings. A lot of attention is paid to the modeling of tribological processes in this precision pair. In [1], a simulation model based on the finite element method was proposed, taking into account the interaction between the elastic-plastic deformation of the irregularities on the piston surface and the surface lubrication state. Seal rings of reciprocating pistons determine sealing failure and affect the performance and safety of aircraft flights [2]. Physical performance testing summarizes the causes of seal failure. It has been established that seal wear leads to a rapid decrease in contact stress and failure of the seal. In [3], a model of the seal degradation process was proposed, which is used to calculate the surface pretreatment contour. The results of the experiments show that the pre-machined contour reduces the wear rate at the initial stage of operation. The tightness of the piston-cylinder coupling is affected by the dynamic characteristics of the cylinder block at operating

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pressure. In [4], a measurement scheme was proposed to accurately determine the dynamic characteristics of a cylinder block.

The radial displacements of the cylinder block surface are measured in two cross sections along perpendicular directions and are measured under various operating conditions. It has been established that the vibrational displacements are commensurate with the displacement of the cylinder block. In [5, 6], an effective method for diagnosing malfunctions of a hydraulic piston pump based on an adaptive neural network is proposed. It is shown that the proposed method has a high performance in diagnosing malfunctions of a hydraulic piston pump. To assess the performance of an axial piston pump, special test benches are created [7] to collect pressure and vibration signals from a real pump at various levels of performance. A model for assessing the performance of axial piston pumps has been developed and a dimensionless performance index has been proposed. In [8], time-varying micromotions of a cylinder are studied. To optimize the tribological properties, texturing of the cylinder surface in axial piston pumps is carried out by applying the optimal design of recess shape.

Due to the power to weight ratio and high efficiency, high speed axial piston pumps are widely used [9] in the aerospace industry. Increasing the rotational speed (up to 10,000 rpm) is considered as an effective method for improving the head capacity [10]. Axial piston pumps are used in various fields, including extreme conditions of deep sea testing [11]. It has been found that leakage increases with increasing sea depth at a certain load because the piston-cylinder gap becomes larger and that the sealing of the gap gradually deteriorates due to a decrease in the sealing factor. As a result of leaks, a reverse flow of the working fluid is formed, according to which the degree of wear of the piston-cylinder coupling is established. In [12], to predict the remaining service life of the pump, a performance reduction model was proposed, which is described by the Wiener process. The effectiveness of the proposed model of destruction of an aircraft hydraulic axial piston pump is experimentally shown. In [13], the influence of oil temperature, spindle speed and load pressure on the operation of a piston couple was studied. A range of operating state parameters has been set, in which the capacity of the pump is sharply reduced. In [14], an analysis was made of the parameters that cause the destruction of the polymer seal on the shaft reciprocating movement unit by changing the pressure from 100 to 400 bar at a shaft rotation speed of 0.15 m/s. It is noted that the maximum wear and deformation was observed at a pressure of 400 bar. It was found that the rise of temperature due to heat generated from friction in the seal zone was responsible for the failure of the seal. A signal processing method was developed [15] based on the analysis of the dependence of the friction coefficient on the generation of sound from friction in the time and frequency domains. The friction coefficients of couples of four polymers and seven metals are predicted in various friction modes over a wide temperature range. It is shown that the method satisfactorily predicts the friction coefficients of various polymer–metal couples. In [16], the thermal deformation properties of compositions based on fluoroplastic-4 with various fillers are studied. Most serially manufactured APPs operate in the range of 1500 - 3000 rpm. An increase in operating speed to 10,000 rpm entails an increase in operating temperature and significantly reduces the wear resistance of friction couples. The service life of a fluoroplastic seal can be significantly increased by radiation treatment [17]. The elastic properties of the elasticity of fluoroplastic seals at elevated temperatures have been little studied.

The purpose of the work is to increase the wear resistance of fluoroplastic seal rings of plungers (Figure 1) of a high-speed axial-piston pump in relation to the operating conditions of a hydraulic drive.

Fig. 1. Axial piston pump plunger with fluoroplastic seal

2 Materials and equipment

A fluoroplastic-4 rod in the initial state (HV 2.3) and after radiation treatment above the melting point (HV 4.8) was selected for the study.

Experiments on kinetic microindentation with a Vickers pyramid were carried out using an MNT_Z_AE_000 hardness tester from CSM Instruments in accordance with ISO/DIS 14577_1:2002.

3 Results

Kinetic microindentation tests are practically the only way to determine the mechanical properties of the surface layers of materials. Figure 2 shows typical diagrams of indenter penetration into the sample under a load of 1 H into the sample surface in the initial state and after radiation treatment. The operating temperature of 80 °C corresponds to the temperature starting from which the effect of temperature on the mechanical properties of fluoroplastic should be taken into account.

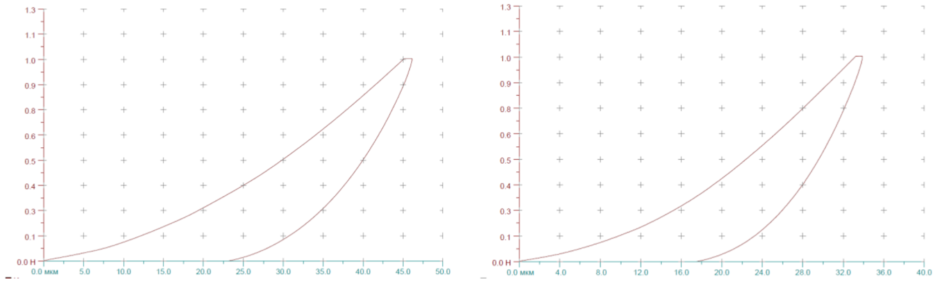

Fig. 2. Typical kinetic diagram of the indentation of the Vickers indenter into fluoroplastic -4 at a temperature of 80°C: 1 – initial state; 2 - radiation hardened.

Despite the external similarity of the diagrams of indenter penetration into the sample at a load of 1 H into the sample surface in the initial state and after radiation treatment, there are large differences. At a working temperature of 80°C in the initial state of the sample, the indentation depth of the indenter is approximately 45 µm, and for the irradiated sample it is 32 µm. Since the surface hardness is inversely proportional to the square of the depth, this confirms the significant effectiveness of hardening radiation treatment.

The mechanical behavior of the surface layer is determined by the diagram of indenter indentation in the coordinate system depth-load on the indenter. The total work done by the indenter is equal to the area of the figure limited by the indentation line of the indenter and

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the horizontal axis of the graph. With an increase in the test temperature, the total work increases monotonically, but not linearly, depending on the change in the hardness of the material. For radiation-hardened fluoroplastic (Figure 3), the total work of indentation is about 2 times greater due to the increase in hardness.

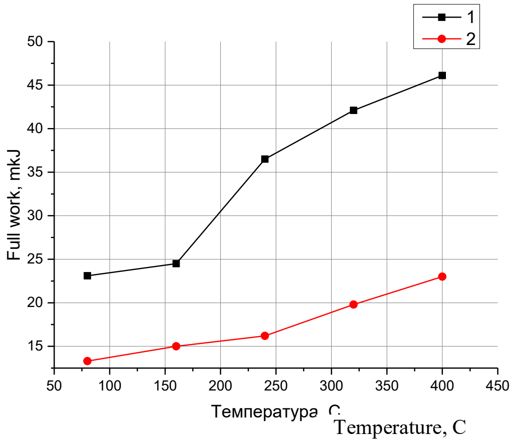

Fig. 3. Effect of temperature on the total work of indentation: 1 – radiation hardened fluoroplastic; 2 - fluoroplastic in the state of delivery

When the indenter is unloaded, part of the work is returned due to the elastic forces. The amount of elastic work is determined by the area of the figure under the unloading curve. After 150 0C, an almost monotonous increase in elastic work begins, and the rate of increase in elastic work is higher for radiation-hardened fluoroplastic (Figure 4).

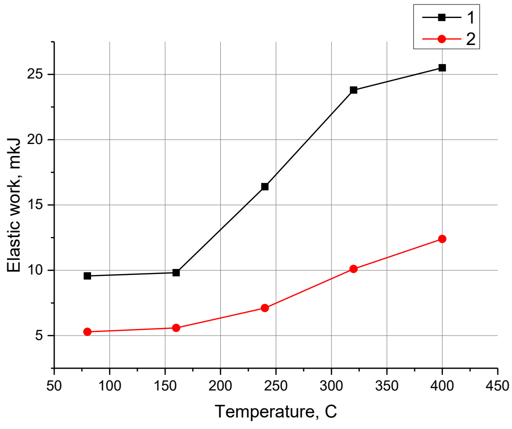

Fig. 4. Effect of temperature on the elastic work of indentation: 1 – radiation hardened fluoroplastic; 2 - fluoroplastic in the state of delivery

The area of the figure between the load and unload curves reflects the amount of irretrievably lost mechanical work of microindentation (Figure 5), which increases with temperature rise.

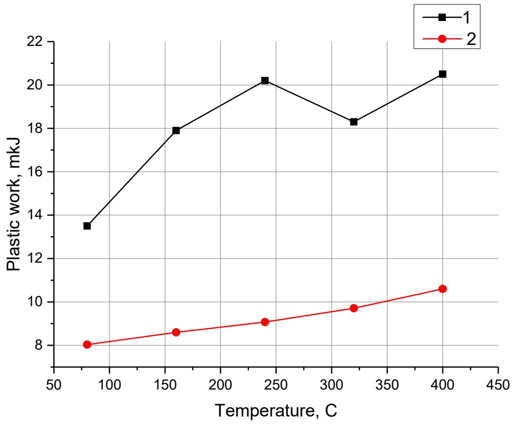

Fig. 5. Effect of temperature on the plastic work of indentation: 1 – radiation hardened fluoroplastic; 2 - Fluoroplastic in the state of delivery

As a rule, it is typical for the same structure of materials a monotonous change in mechanical behavior. The relationship between elastic and plastic work reflects the change in the structure of materials. Figure 6 shows curves of the temperature effect on the change in the ratio between elastic and plastic work. A qualitative change in the structure of the fluoroplastic begins at a temperature of 150 0C, after which the elastic deformations increase significantly. This behavior is equally characteristic of the radiation-hardened fluoroplastic and the original non-hardened one.

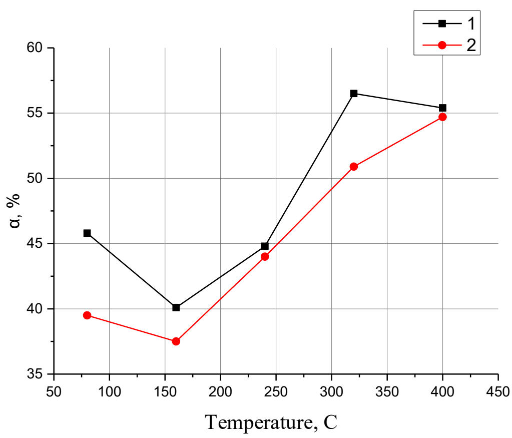

Fig. 6. Effect of temperature on the ratio of elastic and plastic work of indentation: 1 – radiation hardened fluoroplastic; 2 - fluoroplastic in the state of delivery

An increase in the shaft rotation speed in an axial piston pump is promising for improving the power-to-weight ratio, however, it leads to an increase in heat generation in the piston-cylinder coupling from frictional heating, which negatively affects the hardness of fluoroplastic seals and their wear resistance. Up to a temperature of 150 0C, the work of elastic forces practically does not change for radiation-hardened and non-hardened fluoroplastic. The work absorbed by the fluoroplastic monotonically increases due to irreversible plastic deformations. At temperatures above 150 0C, the work of the elastic forces, as well as the forces of plastic deformation, increases almost linearly. At a temperature of 250 0C, the ratio of the elastic and plastic parts is 40% of the total indentation work. When radiation-hardened fluoroplastic reaches 300 0C, the rate of increase in the work of elastic forces decreases, and the work of plastic deformation forces continues to increase monotonically. When the limiting temperature of 400 0C is reached, the ratio of the elastic and plastic parts of the indentation work practically becomes the same at the level of 55%, which gives reason to assume that the radiation hardening effect disappears, and the structures are leveled.

4 Conclusions

1. The thermal deformation characteristics of fluoroplastic-4 in the initial state and after radiation hardening were studied. It has been established that the radiation hardening of fluoroplastic doubles the total work performed by the indenter during kinetic microindentation and the work of elastic forces, which guarantees an increase in the standard work of the piston-cylinder coupling until the limiting value of working fluid leakage is reached.
2. It has been established that the use of radiation hardening treatment of fluoroplastic is promising for increasing the durability of seals. The service life of movable seal ring can also be increased by radiation treatment of the seal as an assembly unit.

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