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WEAR PROCESSES OF HYDRAULIC PLUNGER AND BARREL ASSEMBLIES CONNECTED WITH THE TIME OF THEIR WORK

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Abstract

The article discusses the wear processes of hydraulic plunger assemblies connected with the time of their work and the impact exerted by these processes on the value of parameters of a hydraulic plunger pump. It describes working conditions and loading of a hydraulic plunger assembly. The paper presents also the results of empirical analyses of the wear process of the connection of the plunger base with the working surface of the swivel disk, which is related to time and conditions of its work. It discusses the impact of the loading value and sliding speed on the character and intensity of the wear of the connection between the plunger base and the working surface of a swivel disk. Furthermore, it presents a general characteristic and mechanism responsible for the wear of the hydraulic plunger assembly through oxidation. The article also analyses the impact of the hardness of materials used for producing the hydraulic plunger assembly on the intensity of its wear. Another issue is the dependence of the coefficient of friction in the hydraulic plunger assembly on the contact pressure at different sliding speeds. Finally, the paper discusses the impact of wearing of the cooperating plunger base and the working surface of the swivel disk on the initial parameters of the hydraulic pump at a given working pressure and its volumetric efficiency.

Keywords: *fluid power transmission, pump delivery, volume flow (rate), hydraulic precision pair, avionic technology*

1. Introduction

One of the sources of uncertainty concerning the estimation of durability of a hydraulic air drive is the lack of knowledge on the impact of working conditions of the hydraulic plunger and barrel assemblies on the process of their wear. Even though the knowledge on particular wear mechanisms has developed considerably, there is still insufficient image of this process including the combination, superposition and synergy of various impacts in the conditions of cooperation. This limits the possibility of optimum selection of materials and working conditions of hydraulic plunger and barrel assemblies, as well as the possibility of minimizing their wear.

The wear characteristics of the matching of components of the hydraulic plunger and barrel assembly are defined through the course of processes occurring in the contact area of these components in the presence of hydraulic oil. These processes depend on the loading of the matching of the hydraulic plunger and barrel assembly, sliding speed of components and the path connected with this dislocation (fraction path). It is obvious that wear characteristics cannot be considered as the feature of separated components of the matching of the hydraulic plunger and barrel assembly. The wear characteristics (e.g. resistance to wear) depend on the proper matching of the hydraulic plunger and barrel assembly and mutual impacts defined in the process of cooperation between the components of the hydraulic plunger and barrel assembly, as well as the value of the loading variables of the matching of the hydraulic plunger and barrel assembly, sliding speed of the components and the fraction path. That is the reason why, for example, the coefficient of friction is not a characteristic of the material only, but also of the matching of materials in which friction resistance occurs, whereas it is also dependent on the condition of cooperation.

Resolving the tribological problems in the hydraulic plunger and barrel assemblies requires conducting experimental research whose purpose is to develop methods for minimizing frictions and wear in the phases of design, production and operation. So far, the research involved mainly indicators measured at the initial or final state, i.e. before or after the operation of the hydraulic plunger and barrel assemblies. This provided limited possibilities of acquiring knowledge on the processes occurring in the hydraulic plunger and barrel assemblies.

2. Working conditions and loading of the hydraulic plunger assembly

The hydraulic plunger assembly performs the function of a displacement component of the hydraulic plunger pump. The hydraulic plunger assembly has a work cycle consisting of three stages: filling the working chamber with liquid, transfer of liquid in the working chamber from the suction area (low pressure) to the pumping area (high pressure), displacing of liquid from the working chamber.

The specificity of loading the plunger assembly is simultaneously the mutual interaction of the plunger with two components: surface of the rotor socket and the stop surface of the swivel disk. The plungers make a reciprocating dislocation in the sleeves of the rotor. Apart from the reciprocating movement, the plunger makes also a rotary movement towards the sleeve of the rotor - with variable speed depending on the angle of rotation of the rotor. There is rotation and sliding of the surface of the plunger face towards the stop surface of the swivel disk. Thus, the plunger is affected by friction forces of both mutual interaction with the sleeve and mutual interaction of the plunger with the stop component of the swivel disk.

During the work, the hydraulic plunger assembly is affected by forces whose diagram is shown in Fig. 1.

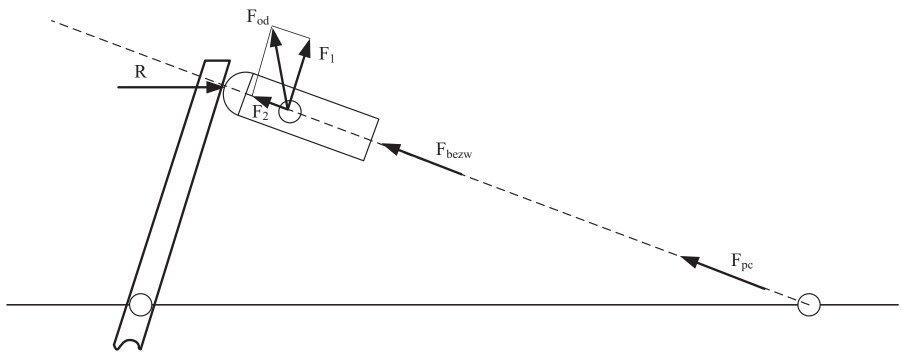

Fig. 1. Diagram of loading the hydraulic plunger assembly: F_{pc} – pressure force of the working liquid; F_{bezw} – inertial force by relative movement; F_{od} – centrifugal force; R – reaction force of the plunger face; F_1 and F_2 – components of the centrifugal force

When pressing the fluid through the plunger, it is affected along axis by pressure force of the working liquid F_{pc}, inertial force by relative movement F_{bezw}. In the radial direction passing from the rotation axis through the centre of gravity of the plunger, there is the centrifugal force F_{od}. In the contact point of the plunger face and the surface of the swivel disk, there is the reaction force R acting on the direction of radium of the plunger. The pressure force of the liquid, acting on the plunger, constitutes the resultant force of pressure of the liquid acting from the side of a pumping main and from the opposite side of the plunger - from the fuselage area. The centrifugal force may be divided into two components: F_1 and F_2. The force F_1 acts on the plunger in the radial direction and presses it against the surface of the sleeve. The value of this component force determines the fraction force in the plunger assembly: $F_{tr1} = \mu F_1$, whereas μ is the coefficient of friction of the plunger in the sleeve socket. The component of the reaction force R is also responsible for lateral pressing of the plunger against the surface of the sleeve. The component of the centrifugal force F_2

acts in the direction of the plunger's axis and presses it against the swivel disk. Due to the rotation of the pump rotor together with the plunger, as well as the change of the pressure of the working liquid, the values of contact tensions between the plungers and the swivel disk change cyclically in the process of work.

The hydraulic plungers assemblies used in pumps or hydraulic rotary engines are characterized by the following features:

1) continuous reciprocating movement of the plungers towards the cylinder with the stroke from a few millimetres to a few centimetres, with the speed resulting from the multiplicity of the rotating speed of lifting system (of the drive shaft),
2) firm radial pressures between the plunger and the surface of the steering swivel disk,
3) work in the conditions of complex matching of the working loadings and mutual dislocation of the cooperating fraction surfaces, with the sliding speed changing according to the angle of rotation of the rotor,
4) wear of plunger's assemblies is connected with the wear of the surfaces of plunger faces and the steering swivel disk.

3. Wear processes in the hydraulic plungers assemblies

The connection of the plunger base and the surface of the swivel disk is a troublesome mechanism of the hydraulic plunger pumps (Fig. 2). The character and intensity of the wear of the plunger base and the surface of the swivel disk (Fig. 3) depend predominantly on value of the sliding speed, axial pressures and hardness of the material of the two components.

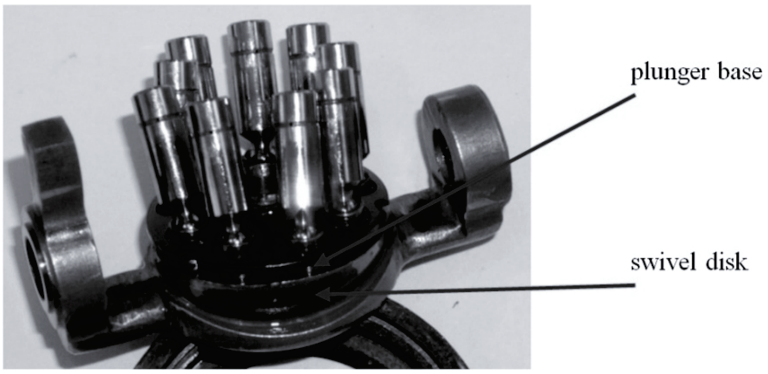

Fig. 2. Connection of the plunger base and the working surface of the swivel disk in the hydraulic plunger pump

Fig. 3. Working surface of the steering swivel disk in the hydraulic plunger pump

To determine the impact of the speed of mutual sliding of the components of the hydraulic plunger assembly on its wear, there were conducted tests concerning the friction matchings of the plunger faces made of chrome-nickel steel 12HN3A (hardness of working surfaces HRC = 60), chrome steel HWG (hardness of working surfaces HRC = 58) and chrome-nickel-wolfram steel 18HNWA (hardness of working surfaces HRC = 62) cooperating with the steering swivel disk made of steel EI-928: hardness HRC = 60 in the environment of hydraulic oil AeroShell Fluid-41 in the temperature of approx. 293 K and the pressures $P_{oś}$ = 100 N, 600 N, 1400 N.

The Fig. 4 presents the dependence of wear and coefficient of friction on the sliding speed for the matching of the friction assembly of the plunger face made of steel HWG with the swivel disk made of steel EI-928 at the pressures $P_{oś}$ = 100 N, 600 N, 1400 N. The Fig. 5 shows the dependence of wear on the sliding speed for the matching of the friction assembly of the plunger face made of steel 12HN3A with the swivel disk made of steel EI-928 at the pressures $P_{oś}$ = 1400 N, 600 N, 100 N. The Fig. 6 presents the dependence of wear on the sliding speed for the matching of the friction assembly of the plunger face made of steel 18HNWA with the swivel disk made of steel EI-928 at the pressures $P_{oś}$ = 100 N, 600 N, 1400 N.

According to the graphs presented in the Fig. 4a, 5a and 6a, the wear of the ball plunger face cooperating with the swivel disk in the environment of hydraulic oil is lower at higher sliding speeds. Moreover, the Fig. 4a, 5a and 6a, show that the greater pressure $P_{oś}$ is connected with the greater wear of the ball plunger face cooperating with the swivel disk.

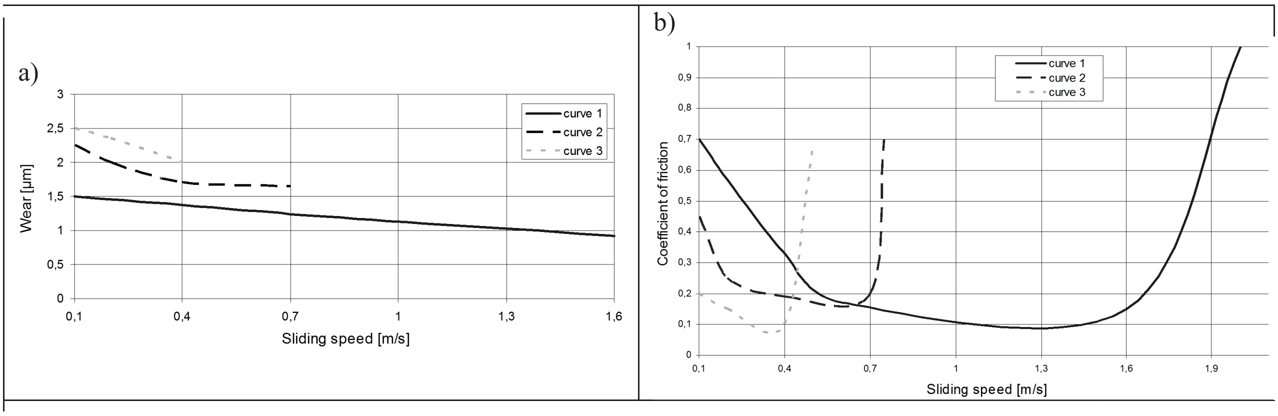

Fig. 4. Dependence of wear (a) and the coefficient of friction (b) on the sliding speed for the matching of the friction assembly of the ball plunger face made of steel HWG with the swivel disk made of steel EI-928; 1-pressure $P_{oś}$ = 100 N, 2- pressure $P_{oś}$ = 1400 N, 3-pressure $P_{oś}$ = 600 N

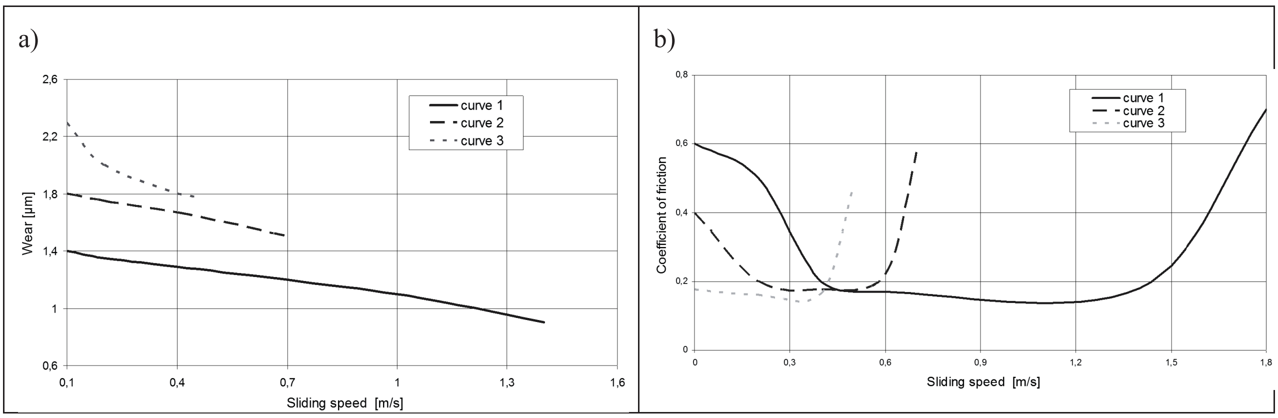

Fig. 5. Dependence of wear (a) and the coefficient of friction (b) on the sliding speed for the matching of the friction assembly of the ball plunger face made of steel 12HN3A with the swivel disk made of steel EI-928; 1-pressure $P_{oś}$ = 100 N, 2- pressure $P_{oś}$ = 600 N, 3- pressure $P_{oś}$ = 1400 N

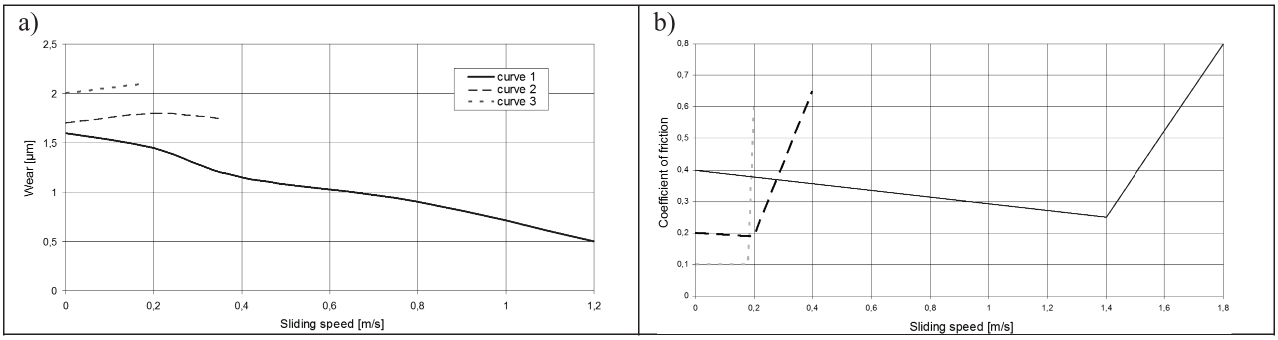

Fig. 6. Dependence of wear on the sliding speed for the matching of the friction assembly of the ball plunger face made of steel 18HNWA with the swivel disk made of steel EI-928; 1-pressure $P_{oś}$ = 100 N, 2- pressure $P_{oś}$ = 600 N, 3- pressure $P_{oś}$ = 1400 N

The graphs in the Fig. 4a, 5a and 6a concern the range of loading and sliding speeds where in the connection of the plunger base and the surface of the swivel disk there is the wear occurring due to oxidation. The wear of the hydraulic plunger assembly occurring due to oxidation ensures its long working time.

Each matching of materials in the environment of hydraulic oil has its critical sliding speed (Fig. 4b, 5b, 6b) at which the quantitative characteristics of the friction process change progressively. When this critical sliding speed is exceeded, there is a rapid increase of the coefficient of friction (Fig. 4b, 5b, 6b) and, in effect, of wear. After reaching the critical sliding speed, there is triggered the process of adhesive wear and the processes of joining metals start to dominate on the friction surfaces. The increase of the sliding speed leads to the decrease of the value of critical loading at which the joining process is triggered.

The coefficient of friction of the plunger assemblies, taking into consideration the impact of the sliding speed and normal loading in the contact area of the plunger and the swivel area, was determined during the tests conducted on a laboratory stand. The dependence of the coefficient of friction in the plunger assembly on the contact pressure in hydraulic oil AeroShell Fluid 41 at the sliding speed of 1.17m/s, 1.53 m/s, 1.85 m/s, 3.36 m/s are shown in Fig. 7. In the case of joining, the coefficient of friction reaches the value 0.8, which rapidly increase the level of shear stresses in the material of a surface layer of the plunger [1].

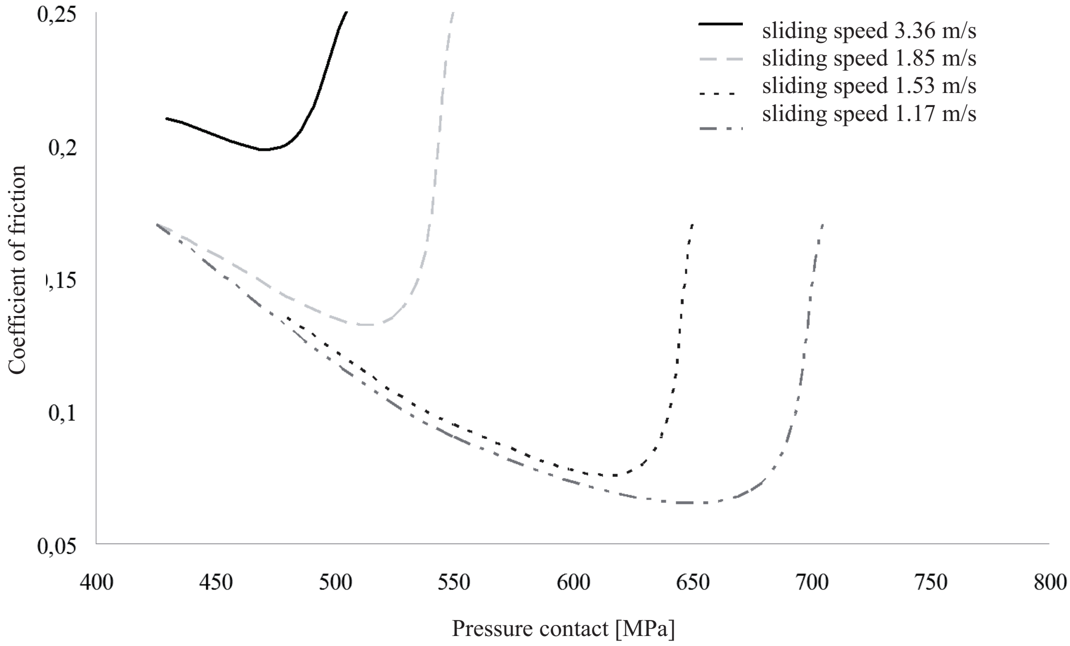

Fig. 7. Dependence of the coefficient of friction in the plunger assembly on the contact pressure at different sliding speeds

The properties of the materials used for producing the assembly have an effect on the wear processes occurring in the hydraulic plunger assembly. To determine the impact of the type and material of the hydraulic assembly on the wear process, there were conducted tests of the plungers made of alloy steel HWG, 12HN3A and 18HNWA of various degrees of hardness which cooperate with the swivel disk made of steel EI-928 that has the hardness HRC = 60 in the environment of hydraulic oil AeroShell Fluid-41 in the temperature of approx. 293 K. The tests also helped to determine the wear of plunger faces. The results of testing are shown in Tab. 1. The tests were conducted for 50 working hours for each plunger at the sliding speed of 1.8 m/s and the pressure of 200 N. The wear was evaluated on the basis of the change of the plunger's weight and diameter of the plunger face. The achieved data were compared to the wear of a plunger made of steel HWG of the hardness HRC = 58, whereas it was assumed that the wear coefficient is equal to one. The data presented in Tab. 1 show that the wear of the hydraulic plunger assembly depends on the type and hardness of the used material.

Tab. 1. Wear of plunger faces made of different kinds of steel

Indicator	Steel brand				
	HWG	12HN3A	HWG	18HNWA	12HN3A
Hardness - HRC	58	60	62	62	62
Relative coefficient of resistance to wear	1.0	1.2	1.3	1.5	1.7

The value of wear of the plunger faces and working surfaces of the steering swivel disk was tested in the plunger pump of variable efficiency in long-lasing station tests. The wear of the plunger face made of steel HWG and the working surface of the steering swivel disk made of steel EI-928 was measured periodically (treating the dimensions of these components taken before the test as the reference basis) by means of the measurement of the height of the plungers and profilers removed by the profilometer produced by the Taylor-Hobson company. The hydraulic pump pushed the hydraulic oil AeroShell Fluid-41 in a closed circuit: from the tank through the hydraulic filters (exact cleaning) and the proportional valve (loading of the hydraulic pump) to the tank. The results of one of the tests on the wear of the ball plunger face and the working surfaces of the steering swivel disk in the hydraulic pump, depending on the working time, are shown in Tab. 2 and Fig. 8 and 9.

Tab. 2. Wear of the plunger face and the working surface of the steering swivel disk in the hydraulic pump, depending on the time of its work

Hydraulic plunger assembly	IU	Working time [h]							
		10	20	30	50	70	100	150	200
Wear of the plunger face	[μm]	23.5	34	43.1	58.7	72.3	88	109	131.3
Wear of the working surface of the steering swivel disk	[μm]	1.5	1.7	2.0	2.0	2.5	3.0	3.5	4.5
Average speed of wear of the plunger	[μm/min x 10^{-4}]	180	167	142	130	110	90	70	70

Due to the kinematics of the movement of the plunger face towards the working surface of the steering swivel disk, it is known that the actual contact point is displaced in relation to the plunger's axis and moves on the plunger cap, depending on the angle of rotation of the rotor (at the established angle of lean of the swivel disk) in the radial direction. When taking the successive positions, it draws a closed circuit. Because of these reasons, the ball plunger face and the working surface of the steering swivel disk get worn in a specific way in particular places.

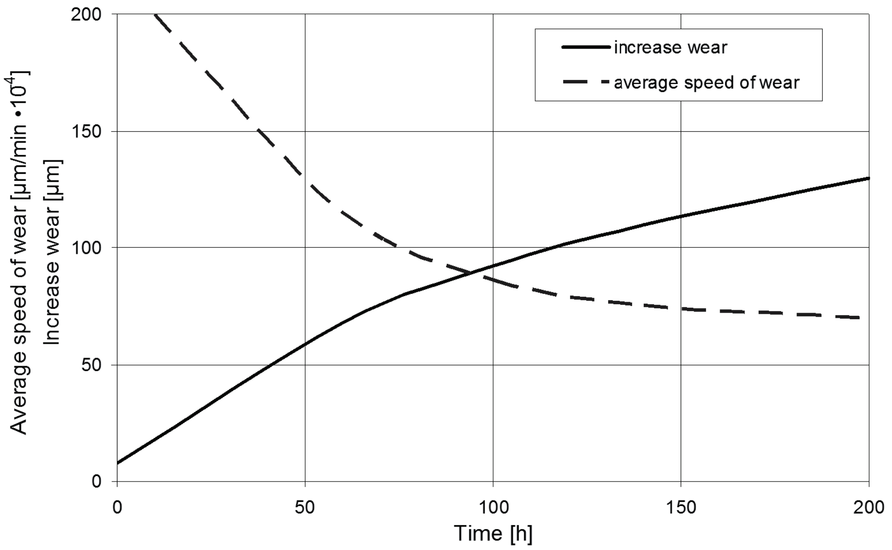

Fig. 8. Change of the wear of the ball plunger face in the pump NP-34, depending on the working time (one of the result achieved during the stand tests)

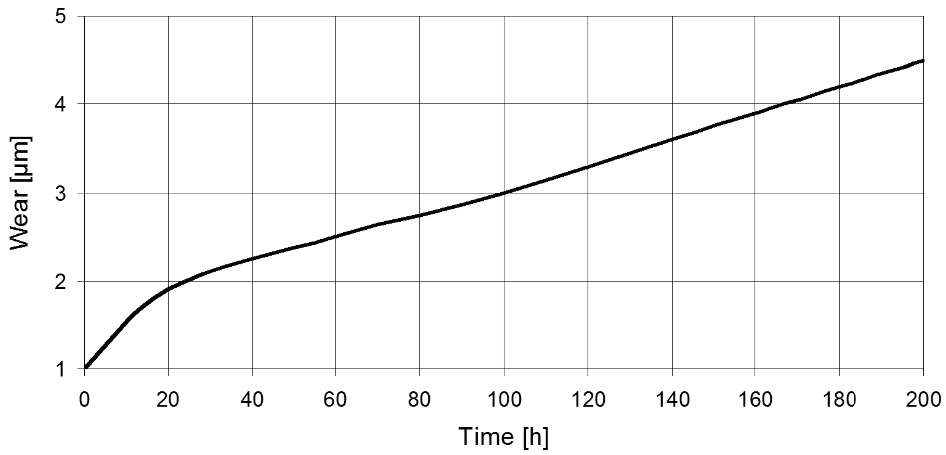

Fig. 9. Change of the wear of the working surface of the steering swivel disk in the pump NP-34, depending on the working time (one of the result achieved during the station tests)

The friction processes of metals in the environment of working liquid are accompanied by intensive creation of secondary structures (i.e. products of the physico-chemical environmental influence and metal in the form of oxides, sulphides, carbides, white non-etching layers, as well as organic substances resulting from thermal processes, oxidation and polymerization) on the surfaces of friction matchings [2-4]. These structures constitute a positive gradient of mechanical properties of the surface layer. Here, each matching of metal, range, kind of friction and features of the environment has a determined specific set of secondary structures determined by the friction forces, character of tribological processes and the degree of wear. Secondary structures are created due to simultaneous course of the processes of deformation, diffusion of substances from the surrounding and chemical reactions. These processes are responsible for the changes of the chemical composition and structure of the surface layer. Thus, it may be said that the resistance to wear of a metal depends, to a great extent, on the composition and properties of the secondary structures on the surfaces on which the friction processes occur. On the working surfaces of the plunger assembly, the secondary structures may be observed in the form of a distinct layer, more or less permanently connected with the original material of varying colour from light brown to green-blue. The colour indicates the differences in the chemical composition of the surface layer created by these structures. It may be presumed that on the friction surfaces of the components in the plunger assembly there are products of the interaction of iron and chromium with oxygen, sulphur and carbon. The colour depends on which product is dominant on the surface layer.

To determine the impact of different matchings of materials used for the production of the plunger and track of the steering swivel disk, there were collected data concerning the wear of these matchings after 200 hours of work of the hydraulic pumps on a test stand and on planes. The plungers in these pumps were made of steel HWG and the tracks of the steering swivel disk of steel EI-928 or EI-347S. The juxtaposition of values of average wear of the components of the plunger assembly in the pumps of the NP-34 type at various matchings of materials in stand tests and during the exploitation in planes within 200 hours was presented in Tab. 3.

Tab. 3. Average wear of the components of the plunger assembly in the pumps of the NP-34 type at various matchings of materials in stand tests and during the exploitation within 200 hours

Type of work	Value of wear [μm]			
	Matching of materials: plunger - steel HWG, track of the steering swivel disk - steel EI-347S		Matching of materials: plunger - steel HWG, track of the steering swivel disk - steel EI-928	
	Plunger face	Track of the swivel disk	Plunger face	Track of the swivel disk
On a testing stand	0.260	0.008	0.034-0.040	0.012
	0.190	0.008	0.025-0.029	0.010
	0.220	0.010	0.030-0.032	0.12
On the plain during the work	0.200	0.021	0.045-0.062	0.023
	0.48-0.050	0.014	0.090-0.110	0.028
	0.37-0.039	0.025	0.061-0.072	0.020
	0.56-0.59	0.016	0.072-0.088	0.027

The mentioned data show that the matching of materials used in the plunger assembly plays a vital role in ensuring proper resistance to wear of its components when working in the environment of hydraulic oil. An increase of seven times is observed when referring to the degree of wear of the plunger face made of steel HWG cooperating with the track of the steering swivel disk made of steel EI-347 - in comparison to the wear of plunger faces made of steel HWG cooperating with the track of the steering swivel disk made of steel EI-928. Here, the wear of the track of the steering swivel disk is comparable in both cases. Moreover, the wear observed in pumps working in natural exploitation conditions is higher in comparison to the wear of components of the plunger assembly in pumps working on a test stand. This proves that the working conditions during normal exploitation are considerably harder than it was assumed in stand tests.

The analysis of forces acting on the plunger during the work of the hydraulic plunger assembly shows that it is pressed to the wall of the rotor's cylinder with a side cylindrical surface - the force used here is the sum of a component radial centrifugal force of inertia (of the plunger) and a component radial force of reaction (of the swivel disk). The values of these forces and the coefficient of friction of the matched materials in hydraulic oil determine the value of the force of friction in a tribological node of the plunger assembly, as well as the intensity of wear of its components. On the basis of observations and analyses of the character and wear of the working surfaces of the hydraulic plunger assembly of hydraulic pumps used in aviation, it may be stated that the processes of wear resulting from oxidation are dominant tribological processes in this node.

The wear of the cooperating plunger base and the working surface of the swivel disk have a direct effect on the initial parameters of hydraulic displacement pumps, i.e. the efficiency of a hydraulic pump at a given working pressure and its volumetric efficiency. Dependence of the efficiency of the hydraulic pump on pressure for the working time of the hydraulic pump - 10 hours and 1000 hours - is shown in Fig. 10. Dependence of the efficiency of the hydraulic pump on a rotational speed of its drive shaft for the working time of the hydraulic pump - 10 hours and 1000 hours - is shown in Fig. 11. These values were achieved in the dominant process of wear of hydraulic plunger assemblies through oxidation.

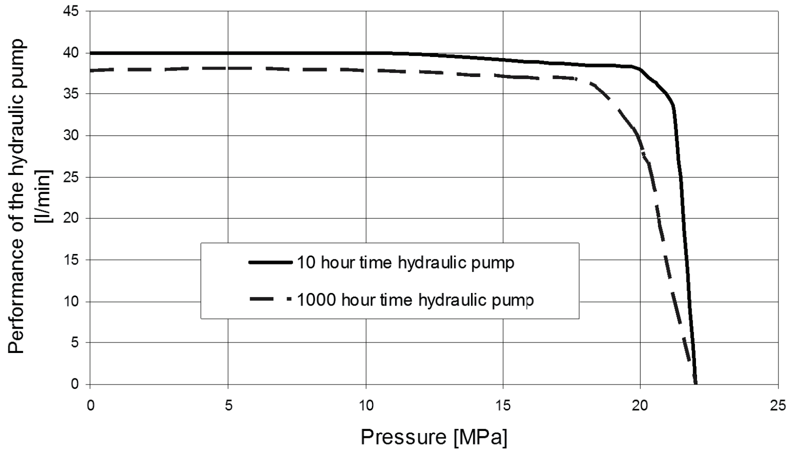

Fig. 10. Dependence of the efficiency of the hydraulic pump on pressure

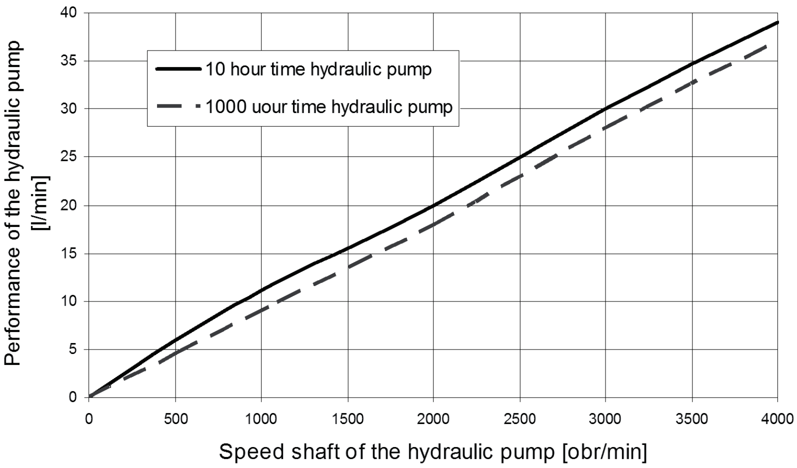

Fig. 11. Dependence of the efficiency of the hydraulic pump on the rotational speed of its drive shaft

4. Conclusions

1) A dominant process of wear of the components of hydraulic plunger assemblies is the wear due to oxidation. There must be proper conditions in which the process of recreating a protective shield of secondary structures on cooperating surfaces unfolds in friction faster than the process of their destruction.
2) The character and intensity of wear of the components of the hydraulic plunger assembly depend predominantly on:
– hardness of the material used in the hydraulic assembly,
– working conditions (surface pressures, values of sliding speeds).
3) The durability of the hydraulic plunger assembly is conditional on the dominance of the process of wear through oxidation during its work. It ensures low intensity of wear of the cooperating surfaces. The dominance of this process of wear is conditional mainly on maintaining (during the work) of the sliding speed of the components of the hydraulic plunger and barrel assembly below the critical value. When the sliding speed is over the critical value, then there is a progressive and rapid change of quantitative characteristics of the processes of wear concerning the friction surfaces of the plunger assembly's components.

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