Research of synthetic corundum in plunger pairs of power hydraulics

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Abstract. The development of hydraulic technologies requires the use of new structural materials. The study used the main provisions of the theory of positive displacement hydraulic machines and hydraulic drives and methods for their solution using multiphysics software. The article presents the results of a comparative analysis of the performance of plunger pairs made of synthetic corundum in hydraulic machines of power drives. The effect of using synthetic corundum in hydraulic power drives is determined. Analysis of the obtained results makes it possible to conclude that when using synthetic sapphire as a plunger material, taking into account the preservation of structural geometry, maximum stresses are reduced by 4.7%, contact stresses by 4.7%, and deformation by 44%, with a decrease in weight by 49%.

1. Introduction

Pilotless vehicles are characterized by stringent requirements for weight and dimensions, as well as expanding the range of external loads (power, temperature, vibration, etc.) - due to the lack of the need to ensure comfortable working conditions for operators and passengers. These factors lead to the need for a more thorough study of structures and the use of modern means of their analysis and synthesis.

A decrease in weight and size characteristics with an increase in drive power indicators is an urgent problem of modern drive engineering. Solutions in this direction expand the scope of application of drive technology [1-3].

The development of modern technologies requires new construction materials that surpass traditional ones in strength, elasticity, environmental friendliness and other properties [4]. In study [5], the authors note that the interdependence of increasing energy efficiency and the development of digital hydraulic technologies.

The areas of development of hydraulic technologies that have arisen in recent decades are mainly focused on the following [6]: energy efficiency (reduced flow forces, lower pressure losses, higher efficiency), suppression of noise, reduced tank volumes, higher pressure level and less installation space,
improved material and oil properties, increased availability and preventive maintenance, ease of use (on-board electronics, commissioning software), security.

For hydraulic components of drives, one of the directions of development of operational characteristics was the use as structural material – technical ceramics, and specifically – synthetic corundum (leucosapphire).

Low coefficients of friction and thermal expansion make it possible to increase the volumetric efficiency significantly reduce the mechanical losses and heat generation of hydraulic devices, which is reflected in a decrease in their weight and dimensions and an increase in power density. This stimulates the growing demand for such devices for hydraulic drives, especially used in unmanned vehicles.

The development of industries, especially aerospace, as well as drive technology and materials science, allows you to take advantage of the most innovative materials. In aviation, polymers and composites are widely used [4]. The use of synthetic corundum in hydraulics is still limited to metering pumps [7] and control system equipment [8]. A separate area of research [9] is in the ballistic optic elements of the fuselage made of sapphire.

The development of research topic is assumed in the direction of experimental tests of a hydraulic machine with a leukosapphire plunger group. The purpose of the experiments is to obtain endurance characteristics and build a fatigue curve for the plunger group in close to real operating conditions.

Aim of work is to study the effect of using leucosapphires as a structural material for tribopairs of power hydraulics.

The studies are used the main provisions of the theory of volumetric hydraulic machines and hydraulic drives, fluid and gas mechanics, theoretical mechanics, the theory of machines and mechanisms, machine details, the theory of ordinary differential equations and equations in partial derivatives, as well as methods of their solutions, methods of simulation and mathematical modeling. The reliability and validity of the obtained scientific results are guaranteed by the correct use of the known scientific provisions of mathematics, mechanics, hydraulics, verification of the results of modeling with experimental data.

The basic element of the power drive in aviation engineering is axial-plunger hydraulic machines (figure 1). They have the best specific power, high control smoothness, and simple interfacing with digital control systems.

![Figure 1. Design of working mechanism of an axial-plunger hydraulic machine.](image)

Hydraulic machine parameters: productivity 33 cm$^3$/rev, working pressure 21 MPa (maximum 25 MPa), rotational speed (max) 3000 rpm.
Develop the topics planned in the direction of fatigue fracture research of products of hydraulic machines made of leucosapphire [10-13].

2. Methods and materials
The choice of the design diagram of the hydraulic machine itself and design versions of its main units and parts is justified by the greatest distribution of this solution among manufacturers and consumers of hydraulic power drive. For the prototype of the hydraulic machine, a large statistical information has been accumulated on operating conditions, characteristics of operation under various conditions and failures (their types, causes and localization [14]), mathematical [15], simulation [16] and virtual models of thermohydromechanical processes [17] have been developed and verified.

The main unit of the hydraulic machine, the plunger, was selected for research (figure 2). Pn is set as initial data, Pf is determined by computational fluid dynamics analysis (CFD).

![Figure 2. Typical hydraulic machine plunger design with hydrostatic unloading: 1 – piston, 2 – hydrostatic support of the piston, 3 – cylinder block bushing, 4 – support disc, Pn is the working pressure of the hydraulic machine, Pf – the pressure of the hydrostatic support of the plunger.]

Design parameters: plunger diameter d = 15 mm, plunger stroke h = 20 mm, plunger length L = 58 mm.

At this, the most responsible unit, a comparative analysis of the operability of the plunger pair of the axial-plunger hydraulic machine, made of leucosapphire and standard design in multidisciplinary software, was carried out.

The calculation scheme shown in figure 3 was developed for the analysis.

![Figure 3. Finite element model of plunger assembly.]

The mixed finite element network is formed by bricks and tetrahedrons with condensation. A finite element network of elements of the brick type provides a better solution to contact problems, and of elements of the tetrahedron type - a better description of the initial geometry [18]. The use of a mixed network provides minimal difference between the design and finite element models. In the model shown in Figure 3, the maximum element size is 0.5 mm. The total number of elements of near 170,000.
The initial data for research were: the kinematics working mechanism of an axial-plunger hydraulic machine, load characteristics, properties of materials.

The boundary conditions are the contact interactions of the cylinder block sleeve, the hydrostatic support of the plunger and the supporting disk. The contact model is surface-to-surface with inconsistent meshes. The friction model is viscous [19].

The pressure of the working fluid is applied as a load to the corresponding wetted surfaces. The value of the fluid pressure \( P = 21 \text{ MPa} \). The studies were carried out at a constant pressure value and its change over time (according to the indicator diagram of the hydraulic machine). The centrifugal forces on the piston unit and on the hydraulic fluid were taken into account as loads.

Material properties of the investigated object. For standard design – platter and plunger – Steel 50HFA (analogue AISI: 6150 or DIN: GS-50CrV4), cylinder block bushing and hydrostatic support – Brass LMts58-2 (analogue DIN: CuZn40Mn2). For the structure under study: platter – Steel 50HFA, plunger and cylinder block bushing - leucosapphire, hydrostatic support – Brass LMts58-2.

The model of the leucosapphire material is anisotropic, uniaxial, the direction of the longitudinal axis \((z)\) coincides with the direction of crystal growth.

Mechanical properties of leucosapphire are shown in table 1 [20].

| Name                        | Value       |
|-----------------------------|-------------|
| Strength limits, MPa        |             |
| tensile                     | 275…400     |
| bending                     | 450…895     |
| compression                 | 2000        |
| Elastic modulus, GPa        | 345         |
| Compression modulus, GPa    | 250         |
| Shear modulus, GPa          | 145…175     |
| Poisson's ratio              | 0.27…0.30   |
| (depending on crystallographic orientation) |             |
| Friction coefficient        | 0.1         |

For the basic design of the CAE piston assembly, the model was verified for several types of loads, materials, and operating conditions [21]. All simulation results are located within the range of values obtained during field tests. The maximum difference between the simulation results and the average value of full-scale tests is 2% (At the maximum values of the parameters of pressure, piston stroke and technological gap). The simulation results of the model with new materials will be verified by the forthcoming tests.

The simulation was carried out in the Autodesk Simulation Multiphysics software package [18]. ASPRO 2012 version. Serial number: 392-06399218.

3. Results and discussion

3.1. Standard design

Structural stresses are presented in figure 4. The maximum stress in the neck of the plunger sphere is \( \sigma = 262 \text{ MPa} \) (determines the strength and fatigue failure of the structure), the maximum contact stresses of the plunger with the sleeve \( \sigma = 192 \text{ MPa} \) (determines the wear value of the friction pair).
Deformation (offset relative to the original contour) of the structure (figure 5).

The maximum deformation (offset from the original contour) was about 0.1 mm (taking into account a gap of 10 μm).

3.2. New design with sapphire plunger and cylinder block bushing

Structural stresses are presented in figure 6.

The maximum stress is in the neck of the plunger sphere is $\sigma = 250$ MPa, the maximum contact stresses of the plunger with the sleeve $\sigma = 183$ MPa.

Deformation of the structure is presented in figure 7. The maximum deformation (offset from the original contour) was about 0.056 mm (0 μm gap).
Figure 7. Simulation results. Deformation of the leucosapphire plunger structure.

The used CAE-model and its results were verified on the standard design and traditional materials [21]. Analysis of the obtained results makes it possible to conclude that when using synthetic sapphire as a plunger material, taking into account the preservation of structural geometry, maximum stresses are reduced by 4.7%, contact stresses by 4.7%, and deformation by 44%, with a decrease in weight by 49%.

4. Conclusion
The creation of innovative products requires the use of innovative materials and development technologies. In hydraulic drive engineering, one of the directions of development has become the use of synthetic ceramics as structural materials, specifically corundum - leucosapphire. As a result of the research, it was determined that replacing the material of the structural unit ‘plunger’ would improve the technical parameters of the product: the dynamics of the lightweight running gear, the reliability and durability of the plunger, and the wear resistance of tribopairs.

For a better modernization of the tribopairs of hydraulic machines of power hydraulics, additional structural study is required, aimed at changing the geometric appearance of the plunger group. As a result of constructive study, 1.5-2 times improvement in operational characteristics should be expected.

The paper presents the results of modeling the functioning of plunger pairs made of synthetic corundum in hydraulic machines of power drives. A comparison with the simulation results verified the same parts made of classical construction materials. Detected effect of the use of synthetic corundum to power hydraulic actuators.

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