Perspectives using synthetic corundum in hydraulic drives

A V Puzanov1,*, A L Simakov1, O V Kosorukova2 and V V Kotov3

1Department of Instrumentation, Kovrov State Technological Academy named after V A Degtyarev, 19 Mayakovskiy Street, Kovrov, 601910, Russia
2Department of Hydraulic Drive and Hydro-Pneumatic Automatics, Kovrov State Technological Academy named after V A Degtyarev, 19 Mayakovskiy Street, 601910, Kovrov, Russia
3Department of Applied Mathematics and Computer-Aided Design Systems, Kovrov State Technological Academy named after V A Degtyarev, 19 Mayakovskiy Street, 601910, Kovrov, Russia

*E-mail: puzanov@dksta.ru

Abstract. The paper considers the perspectives for the use and scope of application of plunger pairs made of synthetic corundum in hydraulic control systems and power drives. The effect of the influence of the use of synthetic corundum in control systems and power drives of hydraulic systems of aircraft has been determined - increasing efficiency and dynamics by lowering the friction factor of 2-3, a decrease in the gaps to 0, increase the operating temperature range, and a weight loss of 10-15%. An approach to the analysis of design options for updated elements of hydraulic drives is formulated.

1. Introduction
Components of hydrogenated drives are characterized by high specific power, stepless control, and high efficiency [1-4]. Hydraulic components of control systems and power drives of aircraft operate under different operating conditions and, accordingly, they are subject to different requirements. Power hydraulics interacts with an object or the external environment. The hydraulic drive of aviation equipment and its components are influenced by force factors, vibration, temperature, etc. All impacts are characterized by a high degree of uncertainty, a wide range of possible values, their interdependence and influence on internal processes in hydraulic drives. From the analysis of the literature, it follows that the working processes of hydraulic power drives of aviation technology involve highly dynamic and impact loads in a wide range of temperatures.

Hydraulics of control systems, as a rule, is isolated from the external environment, it is less influenced by external factors. But the components of the control system are subject to more stringent requirements for accuracy and sensitivity (especially for tracking systems).

Thus, the main requirements for power hydraulics are low weight and dimensions and high power (high level of working pressure and / or speeds of rotation or movement of the managed object). The main requirements for the hydraulics of control systems are high efficiency, sensitivity and speed of reaction to an event, minimal “dead zones”.

The problem of product reliability (especially as important as aviation) is now generally recognized. To ensure the reliability of new products, funds that reach 80-90% of all costs for a technical task are
invested in product reliability funds. And the terms of launching a product into serial production due to
its bringing to the specified values of reliability indicators can increase by 3-5 times or more [5].

Analysis of the literature in recent years indicates the growth trends in the requirements for the
accuracy of dynamic control, intelligence, reliability and survivability of aircraft hydraulic units [6].
Low energy efficiency and high cost are noted as deterrents in solving these problems. The stimulus for
development and at the same time the consumer of intelligent hydraulic systems of the new generation
are the trends of Industry 4.0. Thus, the development of intelligence and environmental friendliness of
hydraulic drives will provide an innovative evolution of traditional hydraulic technologies. The
development of modern technologies requires new construction materials that are superior in strength,
elasticity, environmental friendliness and other properties to traditional ones [5]. In work [6], 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 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), and security [7].

The governing bodies establish specific regional rules for the environmentally friendly production,
processing and disposal of hydraulic products. Although readily biodegradable oils have been available
for over 60 years, mineral-based oils are still the most commonly used. However, continuous
improvement is not only about hydraulic fluids: seals also need to be refined in terms of their
compatibility with hydraulic fluids, new materials and geometries [7]. Thus, the factors that reduce the
environmental friendliness of hydraulic drives include the need to replace the working fluid due to its
contamination with wear products. Therefore, the elimination of tribopairs forming these wear products
will increase the service life of the hydraulic fluid and improve the environmental friendliness of
hydraulic drives (by reducing the proportion of oil).

With the trend towards high speed, high pressure and high power-to-weight ratio of the hydraulic
system, problems such as lower flow rate, lower allowable pressure and severe system dispersion have
also become more prominent. To solve such problems, the researchers have also invested a lot of energy
in optimizing existing digital hydraulic products. Some research results found their application not only
in engineering, but also entered a certain direction in the development of digital hydraulic technology,
digital twins.

Aim of the paper is to study the physical and mechanical properties of synthetic corundum for their
use as a structural material in hydraulic drives. On the basis of the analysis of these options, to determine
the effect of the influence of the use of synthetic corundum in control systems and power drives of
hydraulic systems of aircraft. Formulate an approach to the analysis of design options for updated
elements of hydraulic drives. To achieve the goal we studied characteristic features of operation of
various elements of hydraulic drives, considered modern innovative material – synthetic corundum, its
properties and production technology, and then analyzed the possibility of using hydraulic drives in
various devices as a structural material – technical sapphire (leucosapphire).

2. Experimental part
Single crystals of corundum (natural or synthetic) belong to the ditrigonal-scalenohedral class of trigonal
symmetry $D_{3d}^6 – R3C (L3L3L3PC)$ with symmetry elements [8] of mirror-rotary axis of the sixth order
(axis of inversion of the third order), three axes of the second order perpendicular to it, three planes of
symmetry, perpendicular to the axes of the second order and intersecting along the axis of the higher
order, and center of symmetry.

The spatial arrangement of $O^2-$ ions forms the specificity of the corundum motif. The structure of one
of the types of corundum - sapphire is represented by coordination polyhedra. According to this scheme,
structural elements are depicted not by balls, but by polyhedra formed by lines connecting the centers
of the anions surrounding the cation. The vertices of the polyhedra touch the centers of the anions. The number of vertices of the polyhedron is equal to the coordination number of the cation, and their combination gives an idea of the mutual arrangement of the cations.

Physical and mechanical properties of sapphire [8] are determined by crystal structure and morphology of sapphire. The density, measured by hydrostatic weighing with an accuracy of 0.05%, is 3.97…3.99 g/cm³. The test sample is weighed in the air and in the liquid and its density is determined by comparing the results (the balance Vibra HT 224RCE, Shinko Denshi Co, Japan, ± 0.0001 g). Some impurities (titanium, calcium, etc.), according to literature data, reduce the density. The hardness of sapphire, measured on the Mohs scale is 9, on Knop ranges from 1525-2000, on the Ridgway scale 12.

A special requirement for hydraulic devices is small friction coefficients of conjugated surfaces. For power hydraulics, a low coefficient of friction determines an increase in mechanical efficiency, and for hydraulic devices of control systems – sensitivity and control accuracy.

Hydraulic machines (reversible machines can work as both a pump and a motor) and hydraulic cylinders are considered as objects of power hydraulics. Hydraulic machines provide the transformation of energy from its source to the hydraulic network and from it to the object. The converter of mechanical energy of rotation, used in modern hydraulic systems of aviation and mobile equipment, is an axial-plunger hydraulic machine (figure 1).

Figure 1. Axial piston hydraulic machine.

The converter of hydraulic energy into mechanical energy of linear movement is a hydraulic cylinder (figure 2).

Figure 2. Hydraulic cylinder.

Directional spool valves are considered as equipment for hydraulic drive control systems (figure 3).
3. Results and discussion

Conventional hydraulics will change significantly over the next 10 years. Intelligence, sensors, electronics and software will increasingly be used in complex systems and drives. This will be strongly influenced by trends in IT and automation. Areas that offer potential for industrial hydraulics include compact axles, energy efficiency, and usability. The developments in the new IT-driven automation world will complement the previous key areas of hydraulics.

The friction coefficient of sapphire pairs depends on orientation (figure 4). Figure 4 shows graphs that the basic properties of sapphire tribomechanical pairs depend on the orientation and, consequently, of manufacturing techniques crystals [9].

High rates of specific loads form requirements for the contact strength of mating parts during their interaction - in static and dynamic modes of operation.

Strength limits for various types of tests of sapphire at room temperature:

- Tensile strength: 275…400 MPa (4…6 × 10⁴ psi).
- Bending strength: 450…895 MPa (7…13 × 10⁴ psi).
- Compressive strength: 2 GPa (3 × 10⁵ psi).

Young’s modulus (modulus of elasticity) is the inverse of compliance. For sapphire, the value in various crystallographic directions is different. Young’s modulus also depends on temperature. Currently, calculations most often use a value of 345 GPa (50 × 10⁶ psi).

- Compression module: 250 GPa (36 × 10⁶ psi).
Shear modulus (stiffness modulus): 145 GPa (21 × 10^6 psi) - 175 GPa (26 × 10^6 psi).
Break module: 350 - 690 MPa (5…10 × 10^4 psi).
Poisson's coefficient: 0.27…0.30 and depends on crystallographic orientation.
Melting point: 2323 K.
Boiling point: 3253 K.

The coefficient of linear expansion of the sapphire (α) depends on the temperature and spatial orientation of the crystal (figure 5). The values of α-sapphire, like other thermophysical parameters given in the catalogs, differ significantly. At room temperature T = 295.65 K, the coefficients of linear expansion for the lattice constant are $\alpha_a = 5.22 \times 10^{-6}$ K$^{-1}$; $\alpha_c = 5.92 \times 10^{-6}$ K$^{-1}$.

[Figure 5. Linear expansion factor versus temperature.]

The low coefficient of linear expansion provides small clearances in the joints and thereby increases the hydraulic efficiency over a wide range of temperature changes. The thermal conductivity coefficient ($\lambda$) of sapphire also depends on temperature and orientation. Usually, the values of the thermal conductivity coefficient are used at:
- 298 K, perpendicular to axis C: 30.3 W/(mK), parallel to axis C: 32.5 W/(mK);
- 273 K, 60°-orientation: 46.06 W/(mK);
- 373 K, 60°-orientation: 25.12 W/(mK);
- 673 K, 60°-orientation: 12.56 W/(mK);

Specific heat capacity of sapphire (cp) at 293 K: 0.181…0.187 cal/(gK), at 1273 K: 0.300 cal/(gK).

Most physical and mechanical properties (especially bending strength) depend on the degree of imperfection of the crystal lattice of sapphire, which is determined by the method of growing the crystal, its real growth modes, processing conditions and further relaxation (annealing, etc.).

The methods for evaluating the fatigue life of components are developed and regulated by American Society for Testing and Materials (ASTM International) [10].

As the analysis of the review of the results of tests of leucosapphirs [11,12] in various conditions close to the operating modes of modern hydraulic devices showed, crystal growth using the Kiriopoulos method has significantly better performance. This is due to the better quality of the crystal lattice, in contrast to crystals grown according to the methods of Baghdasarov, Stepanov and others. The main differences are expressed in the absence of block, low dislocation density, fewer defects (bubbles), and low levels of internal stresses, etc. The maximum mechanical strength of leucosapphire can be obtained by growing according to the Kiriopoulos method at slow modes, optical quality control, and subsequent high-temperature annealing (1700 °C and above).

The materials from which the aircraft is made must provide the necessary strength and rigidity of the structure, be environmentally friendly while having less weight to reduce the total weight of the aircraft and increase its efficiency. Improving the dynamics and efficiency of hydraulic technology is realized...
by reducing friction. Table 1 shows the dependence of friction coefficient on the pressure and materials of the tribopairs.

| P, N  | P/S, GPa | Sapphire-steel | Ruby-steel |
|-------|----------|----------------|------------|
| 5     | 1.7      | 0.33/0.13      | 0.40/0.12  |
| 10    | 2.6      | 0.31/0.15      | 0.27/0.15  |
| 15    | 3.0      | 0.28/0.17      | 0.3/0.12   |
| 20    | 3.3      | 0.25/0.15      | 0.28/0.11  |
| 25    | 3.5      | 0.23/0.15      | 0.26/0.12  |
| 30    | 3.7      | 0.22/0.14      | 0.25/0.12  |

* In the numerator – the coefficient of dry friction, in the denominator – in the presence of oil lubrication.

Fatigue properties are the determining factor in assessing the service life of friction units in terms of durability for brittle materials operating under variable loads. The variability of loads in the contact zone during friction is associated with the surface roughness at the micro level, i.e. with the presence of micro protrusions on both rubbing surfaces. With their mutual contact, the fatigue limit of materials is reached rather quickly, which leads to the formation of subsurface and surfaces. With their mutual contact, the fatigue limit of materials is reached rather quickly, which leads to the formation of subsurface and surface cracks and the separation of wear particles (figure 6, 7). Figure 6 reflects the nature of fatigue fractures characteristic of synthetic corundum crystals. Upon closer examination of fracture (figure 7) obviously influence the quality of the surface treatment on the formation of cracks.

![Figure 6](image6.png)

**Figure 6.** Fatigue fracture of a synthetic corundum (left) and high-alloy steel (right).

Images of figures 6 and 7 were obtained by methods of classical materialography [13] on laboratory equipment UIM-23 (LOMO, St. Petersburg, Russia). The nature of the fracture of synthetic corundum (figure 6, left) reflects the specificity of the corundum motif. For comparison, an image of high-alloy steel cracking is shown (figure 6, right).
Comparison of the obtained data for a single crystal of sapphire with a prismatic orientation of the friction plane at dry friction in the same pair with similar data for ceramics shows that for a single crystal the limit number of cycles before surface destruction is $5 \times 10^5$, and for polycrystalline ceramics $\sim 10^5$, i.e. the fatigue limit for a single crystal is 5 times higher [14].

Compared to classic structural materials used in hydraulic drives (Steel 50HFA – analogue AISI: 6150 or DIN: GS-50CrV4 and Brass LMts58-2 – analogue DIN: CuZn40Mn2), products made of synthetic sapphire have a number of advantages (see table 1), allowing get products from new technical and operational levels.

Thus, the effect of the use of synthetic corundum in control systems and power drives of aircraft hydraulic systems is as follows. The use of backlash-free tribopairs made of synthetic corundum makes it possible to increase the volumetric efficiency of the hydraulic apparatus up to 100%, which increases its efficiency. At the same time, the absence of wear products may improve environmental friendliness by increasing the service life of the hydraulic fluid. An unresolved issue is the fatigue strength and impact strength of conjugated synthetic corundum tribopairs. However, a number of works [15] in the field of ballistic strength of fuselage elements made of leucosapphire allows us to consider this trend optimistically.

The analysis of the applicability of synthetic corundum as a structural material of elements of hydraulic systems (hydraulic power drives and their control systems) should contain a mathematical apparatus that takes into account the anisotropy of the material, hydro- and thermomechanical processes and processes of tribotechnics and reliability, as well as take into account environmental aspects.

The use of sapphire tribopairs in hydraulic components has a number of promising advantages: the achievement (development) of new characteristics, the expansion of the field of operation, provides innovative products. Among the advantageous properties of hydraulic drives with parts made of synthetic sapphires are: reduced friction, reduced (to 0) gaps, increased temperature range of operation, reduced weight, reduced contact stresses, etc. Thus, the current direction of expanding the field of application of sapphires in drive engineering is the study of their fatigue characteristics and the degree of effect on them of the operational parameters of the drives.

It is expected that the widespread use of synthetic corundum as a structural material for hydraulic drive elements will contribute to:

- reducing the weight of the aircraft up to 15%;
- improving fuel efficiency;
- increasing the resource;
- reduction of operating and maintenance costs by up to 10% (due to a decrease in the number of structural inspections), as well as due to high corrosion resistance and a longer service life of new materials compared to classical ones.
The use of backlash-free spools with a low coefficient of friction and low sensitivity to temperature changes will increase the sensitivity characteristics, expand the operating temperature range and reduce the hysteresis of the characteristics of hydraulic control systems of aircraft, which is especially important for tracking systems.

For the power elements of the hydraulic drive of aircraft, the same advantages of leucosapphires will make it possible to reduce the area of body parts, and, consequently, their dimensions and weight. Due to its low coefficient of friction, it is possible to increase the relative speeds of mating pairs, thereby increasing the performance characteristics. All this should be reflected in an increase in the specific power of the hydraulic drive as a whole, which is a competitive advantage in the drives of aircraft and mobile equipment (including unmanned vehicles). These assumptions have already been reflected in practical implementation - in dosing pumps of the pharmaceutical industry [16].

The analysis of available scientific and technical sources did not reveal the experimentally obtained fatigue characteristics of sapphire, however, there are studies confirming the dependence of the crystal production quality and its mechanical properties [8,9,12], as well as the similarity in fatigue characteristics with uncut ceramics [17]. Reasonable reduction of vibration and shock loads, prediction of the endurance limit of products of hydraulic components from leucosapphire makes it possible to create elements of hydraulic control systems and a power drive with unique performance characteristics. Due to its low coefficient of friction, it is possible to increase the relative speeds of mating pairs, thereby increasing the power characteristics. Increasing the efficiency of hydraulic devices, their low sensitivity to temperature changes, allows you to reduce the area of body parts, and, consequently, their dimensions and weight.

4. Conclusion

Thus, we can conclude that the work is being carried out in the promising direction of the development of the use of innovative materials in aircraft construction. With the widespread use of such materials, corresponding to advanced world ideas, new samples of aviation technology are created.

The effect of the use of synthetic corundum in control systems and power drives of hydraulic systems of aircraft consists in the use of backlash-free tribopairs made of synthetic corundum, which makes it possible to increase the volumetric efficiency of the hydraulic apparatus up to 100%, and, consequently, increases its efficiency. At the same time, the absence of wear products improves environmental friendliness by increasing the service life of the hydraulic fluid.

An analysis of the applicability of synthetic corundum as a structural material for specific elements of hydraulic systems (hydraulic power drives and their control systems) should contain a mathematical apparatus that takes into account the anisotropy of the material, hydro- and thermomechanical processes and processes of tribotechnics and reliability, as well as take into account environmental aspects [18].

The practical value of the work is in the development and production of hydraulic equipment with new characteristics. The development of the work is planned in the direction of accumulating data on the reliability and service life of synthetic corundum products in hydraulic drives.

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