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Metal-Polymer Materials for Tribotechnical Components of New Type Cardan Shafts

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Keywords: Cardan transmission; antifriction polymer coating; crank joints; movable spline connections; composite materials; polymer matrix material; modifying thermoplastic polymers; wear resistance; microscopic analysis; coatings.

Abstract: This article is dedicated to addressing the following technical and operational issues through the analysis of scientific solutions. We know that failure of some units of the cardan transmission leads to the destruction of the connected units (for example, the drive axles and gearbox reducers) in the presence of a significant imbalance. The large metal volume, vibration activity, low reliability level, and large axial forces arising in the spline connection of the crankshaft are serious drawbacks in the design of most crankshafts, therefore, the issues of improving the design of crankshafts and increasing their reliability level are relevant and require immediate solutions. In solving these problems, the role of materials science and technological aspects is significant, the consideration of which at the stage of designing a cardan transmission ensures achieving optimal operational life.

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1 INTRODUCTION

Significant drawbacks in the designs of cardan transmissions used in domestic automotive and agricultural machinery include excessive metal volume, high vibration activity, insufficient reliability, and large axial forces transmitted to the units connected to the supports.

Tubes are one of the critical structural elements of cardan shafts. They are typically manufactured from high-carbon steel with high precision: the permissible wall thickness variation should not exceed 0.06 mm, and the vibration should not exceed 0.15 mm per linear meter over a 2 m length. The tube must operate reliably under the specified load torque, possess transverse strength, and have maximum specific mass.

For the crankshafts of trucks, thin-walled pipes with an increased internal diameter, electric welded, and rolled pipes are used. Such pipes provide high bending strength and contribute to a reduction in mass. The use of light alloys and polymer composite materials is a promising direction for reducing the mass of pipes (Fig. 1).

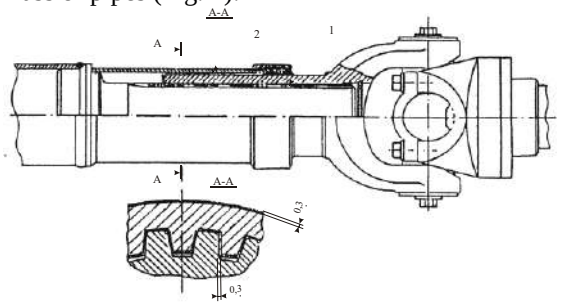


Figure 1: Principal design of a movable spline connection with antifriction polymer coating (1) and a telescopic seal (2).

Due to the lack of developments in our country for composite materials that meet modern requirements in terms of cost, manufacturing technology, and assembly, similar designs are not being used in practice.

Abroad, PA 11 (Rilsan) with a Rilprim sublayer is used for manufacturing antifriction coatings. The coating application technology is quite complex and requires significant labor input and highly skilled personnel. Attempts to replace the expensive PA 11 with domestically produced materials have not been successful due to the low quality of PA 6.

To reduce the moment of inertia of the universal joint relative to the axis of rotation, the distances at the ends of the cross pieces are decreased, while the diameters of the splines are increased, enhancing their load-bearing capacity. Furthermore, to reduce axial clearances in the universal joints, needle bearings are equipped with anti-friction polymer washers located at their base, and several groups of retaining rings are used to secure the bearings in the fork joints (Fig. 2). This significantly reduces the axial clearance in the joints and decreases the vibration activity of the universal joint transmissions during operation, as well as improves the balancing of the shaft.

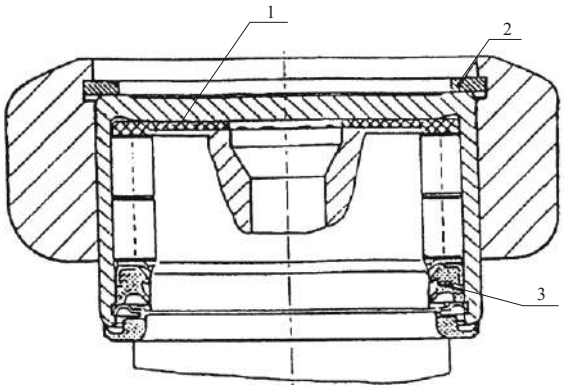


Figure 2: Needle bearing construction with a stamped body made of flat material: 1 - antifriction polymer washer; 2 - locking ring; 3 - seal.

In foreign designs, glass fiber-filled PA 6 (GWB, Germany) and glass-filled composite material Itamid-25 (FMS, Poland) are used as materials for manufacturing polymer washers. Until recently, glass-filled polyamides were not produced in our republic, so the task was to develop a composite material that would not be inferior to the best foreign products in terms of performance characteristics.

Reducing the vibration activity of the crankshaft drives, increasing manufacturing accuracy, reducing the needle size in the bearing assembly to 0.002 mm, and using advanced methods for machining crankshaft parts also significantly influence the increase in their service life.

When ensuring high reliability of crank joints and movable spline connections, improving their tightness remains an important factor. Recently, the use of radial and edge sealing elastic edges has come to the forefront among various solutions.

The radial-edge bearing seal (Fig. 2) is made of polymers that are more resistant to wear and durable compared to rubber, better seal the hinge, and reduce the dimensions of the seals. For example, it is known that polychrome sealants made of polymer materials based on polyurethane are more compact (by 1.5 times shorter than a rubber sealant).

The production of rubber-technical materials is developing in our republic. Therefore, there is an

urgent need to develop a technology for manufacturing sealing products from composite materials based on thermoelastoplasts using advanced methods.

Telescopic seals are effectively used to increase the wear resistance of antifriction polymer coatings on splined joint elements.

The service life of constant-velocity joints installed near the powertrain depends on axial forces, which are determined by the number of suspension points and balls. Therefore, new generations of shafts with articulated drive use constant-velocity joints with six rigid balls and three universal suspension points. During the development of front-wheel drive vehicle production, it was discovered that drive shafts vibrate intensely in certain operating modes. These vibrations are eliminated using inertial dampers.

One of the most vulnerable areas of hinges with equal angular velocities is the protective covers ("dust collectors"). The rubber used in their manufacture can withstand only 80-140 thousand cycles of load at operating temperatures of the vehicle. To ensure the tightness of hinges with equal angular velocities in the new generation of front drives, elastic protective covers made of thermoelastoplast, significantly superior to rubber mixtures in strength, wear resistance, and wear resistance, began to be used. For example, "Heitrel 8105" thermoplastic covers surpass rubber ones 8-10 times in terms of service life. Furthermore, the vacuum effect is not characteristic of such covers; they are more resistant to road mechanical damage.

In our republic, such materials are not produced industrially. Therefore, it is necessary to develop a proprietary composite material based on thermoelastoplast with specified operational characteristics.

2 METHODOLOGIES

The specific operating conditions for products made of thermoplastic materials for structural applications necessitate targeted modification of polymer matrices. This modification leads to a reduction in fundamental drawbacks and often results in thermoplastics acquiring new properties and enhancing their advantages. The main disadvantages of traditional structural thermoplastics include relatively low physical and mechanical characteristics, as well as merely satisfactory tribological and thermophysical properties. These limitations of thermoplastics prevent their use in unmodified form for manufacturing products that need to function across a wide range of temperatures and loads, in various operating conditions, and in both inert and aggressive environments.

The active centers of macromolecules present when aggressively exposed to a polymer material with a chemical structure of chains and synthesis conditions are, as a rule, foci of matrix destruction. In this case, the interaction of the active centers of macromolecules with various reagents of the operating medium (oxygen, low molecular weight products of polymer destruction, moisture, etc.) leads to a decrease in the operational characteristics of the material.

The introduction of activated ingredients using various technological methods, physical influences, or targeted modification of industrial polymers using polymer-oligomeric and polymer-polymer hybrid mixtures as a polymer matrix is the simplest and most effective way to improve the basic operational characteristics of basic polymer binders. Implementation of such an approach is economical from a technological point of view and relatively simple and does not require large expenditures. According to literary sources, filling is the combination of polymers with solid, liquid, gaseous substances, which are relatively uniformly distributed in a volume with a continuous phase.

The introduction of a filler into polymers affects the structural, physical-mechanical, tribotechnical, thermophysical, and other characteristics of the material. The general physical and technical principles of modifying polymer matrices with fillers are based on interfacial phenomena at the polymer-filler interface and the formation of an interfacial layer with a specific structure, differing in volume structure and properties from the base material. The new properties of the polymer matrix are due to effects explained by the influence of the filler particle surface on the movement of macromolecules and the formation of adsorbed polymer layers in the boundary region. As a result, polymer structure formation occurs differently in the binder volume and near the phase boundary. The main changes in systems with fillers, in the absence of chemosorption interaction between the matrix and the filler, are mainly determined by the surface properties of the filler.

To reduce the degradation of the polymer matrix material, modifications are made using chemical and physical methods, as well as combinations of these methods. For the modification of thermoplastic and thermoplastic elastomer polymers, components of inorganic and organic nature with particle sizes

ranging from 2-3 μm to 10-100 μm are used. These include fiberglass, metals and their oxides, carbon materials, crushed rock, wood particles, and others.

Today, the most developed methods for modifying thermoplastic polymers involve alloying them with small polymer additives, both during the synthesis stage and during the addition of solution components that form polymer-polymer or polymer-oligomeric mixtures. For such polymer systems, the flexibility of the components is crucial, determined by their polarization, solubility, chain flexibility, and other characteristics. For example, through copolymerization of 5-25% butadiene or butadiene-styrene rubber and 15-30% styrene acrylonitrile, large-scale ABS plastics are produced, which have several significant advantages over the original polystyrenes (high viscosity, thermal shrinkage, etc.).

An increase in the physical and mechanical properties of alloyed thermoplastics is observed due to the formation of transition layers in the alloying phase of reinforcing aggregates and reinforcing additives within the matrix volume.

By thermomechanical mixing of polymers, compositions with optimal physical and mechanical characteristics are obtained that perform structural functions such as polyamide-polyolefin, polyolefin-divinylstyrene thermoelastoplast, and others.

Among the known polymer mixtures performing a structural function, compositions based on polyamides and polyacitiles are of particular interest. For example, in two-component systems, each with a low concentration, the effect of an anomalous increase in physical and mechanical characteristics has been established, which is caused by the formation of a mixture of fibrous aggregates - ultrafine fibers - that contribute to the strengthening of the polymer base during processing. It has been established that a copolymer base can form in a binary mixture of thermomechanically mixed matrices.

As a doping polymer additive to thermoplastics, oligomers of crosslinking resins - phenol-formaldehyde, imide, organosilicate, polyester, and others - can be used. In this case, a "grid within a grid" structure is formed in the thermoplastic matrix. Oligomers of crosslinking resins can interact with the active groups of the base polymer, leading to an increase in its deformation-strength characteristics and thermo-oxidative stability. In a number of cases, some oligomers exhibit the properties of non-chain stabilizers.

To improve the strength, thermophysical, and tribotechnical properties of structural thermoplastics, along with the aforementioned modification methods, various fillers such as graphite, talc, coke, fiberglass, asbestos, metal powders, and their oxides are used

It is known that the wear resistance of filled compositions increases by several orders of magnitude compared to unfilled ones, and the load-bearing capacity and heat resistance increase by 2-5 times. At the same time, the maximum modification effect can be achieved only with a small amount of filler (5-20 wt. %), which leads to an increase in mechanical characteristics (hardness, strength, relative elongation, and wear resistance).

Thermoplastic polymers filled with high-module carbon fibers have high physical-mechanical and tribotechnical characteristics. In this case, according to the data presented in (Malevich, Ovchinnikov, Boyko, Struk, 1998), the fiber content is 30 wt. At about %, the wear resistance of the composition practically does not depend on the type of polymer matrix, but only on the properties of the fiber, primarily the properties of the surface layer. Materials filled with fibers have high strength, hardness, thermal conductivity, and a low coefficient of friction

Academician N.S. Yenikolopov and his team developed highly filled polymer composite materials (PCM) - norplasts, which contain up to 80-90% mineral fillers, often consisting of highly dispersed particles of crushed rocks. However, processing norplasts requires special technological equipment with high injection pressure parameters, which significantly reduces the efficiency of their use in mechanical engineering.

The presence of fillers in the polymer matrix significantly affects the conditions of their processing and the quality of the products obtained. Studies show that filled thermoplastics can be processed by all available and known methods. In this case, in filled polymers, a decrease or stabilization of contraction, a change in the nature of relaxation processes, and more stable rheological characteristics are often observed.

However, the introduction of even harder fillers into thermoplastics accelerates the aging of the counterweight added as a result of mechanochemical processes at the friction node. The use of fibrous fillers can lead to deterioration of product properties due to the uneven distribution of filler in the polymer mass or its direction.

Thus, many problems of structural polymer materials science can be successfully solved with the optimal selection of fillers and modifiers. The choice of a specific method for obtaining a composite

material with a given characteristic depends on a set of economic, operational, technological, and other aspects.

3 RESULTS AND DISCUSSIONS

One of the main objectives of this research is the development of polymer composite materials (PCM) based on thermoplastics and their mixtures for the design of cardan drives. Increasing the strength, tribotechnical and thermophysical properties of the initial polymer matrices is the main criterion. For the creation of PCM, traditional multi-tonnage polymers produced in domestic industry were used as initial matrices: polyolefins, their copolymers, and polyamides.

The following marks of materials were selected as objects of research:

- PEHD 277-03 (GOST 16338-85);
- PELD 15803-020 (GOST 16337-85);
- PP 21020 (TU6-05-1756-78);
- CEVA 11306-075, 11607-040, 11708-1250 (TU 301-05-56-90);
- PA6 (GOST 6-03-09-93);
- PA11 "Rilsan" manufactured by ELF ATOHEM (France);
- DST (TU 38 103624-80).

Regenerated technological waste obtained from the recycling of polymer-based products was also used as matrices.

The physical-mechanical, tribological, thermophysical, and other characteristics of the thermoplastics and thermoelastoplasts used are presented in numerous reference materials. Some experiments were conducted on samples of basic mixtures of thermoplastic-thermoplastic and thermoplastic-thermoelastoplast types.

For the modification of polymer matrices, ultrafine graphite (UFDG), referred to as carbon charge and containing diamonds, was used, as well as the product of detonation synthesis of high-explosive materials obtained under negative oxygen balance conditions. Some characteristics of the charge are provided in Table 1.

In some experiments, ultrafine diamond, ultrafine silicon oxide, and colloidal copper particles (CM) obtained by thermolysis of copper compounds in a binder solution, as well as K-354 grade carbon black, were used as fillers.

Experimental studies were conducted on samples made of polymer materials and polymer composite materials (PCM) in the form of standard shovels, bars, plates, and other shapes. To reduce the moisture content to a specified level, pre-dried modifiers were incorporated into the composite material by mechanically mixing the polymer powder or granules in a ball mill. To minimize the effect of static charge on the homogeneous distribution of the modifier, the polymer particles were treated with a volatile solvent - either acetone or ethyl alcohol.

Table 1. Comparative characteristics of some types of carbon fillers.

Properties	Modifier indicators			
	Colloidal graphite	Carbon graphite fibers	Technical Carbon (TC)	Carbon charge (UFDG)
Density, g/sm^3	2.7	3.3	2.6	3.2
Dispersity, μm	1-10	20-100	0.1-0.5	0.03-0.05
Particle shape (AFM method)	Plate-like	Fibrous	Spherical	Spherical
Specific surface area, m^2/g	-	-	100	300±30
Crystalline fraction content, %	90	-	-	60-75

Samples for testing were obtained by high-pressure casting in recommended modes in accordance with GOST and TU requirements, as well as by thermopression on fluoroplastic substrates (substrata) on an industrial thermoplastic apparatus. The thermomechanical connection of the components was carried out in screw plasticizer units in modes characteristic of the polymer matrix.

Composite coatings based on thermoplastic polymers were applied in a molten layer using tribostatic spraying methods, after which they were melted in a thermostat in the modes specified in (Struk, 1988) or given in the technological instructions. For obtaining coatings, industrial-produced powder from ELF ATOCHEM (France) or dispersions obtained by cryogenic dispersion of polymer granules were used.

To control the physical-mechanical, adhesion, tribotechnical, and other characteristics of PCM, fillers and modifiers were treated in a special unit

with a corona discharge or a diluted solution of fluorine-containing oligomers of the "Foleox" brand. The composition and structure of the oligomers used are presented in (Ovchinnikov, 1997).

The study of the features of the physicochemical composition of polymers, PCMs, and modifiers was carried out according to generally accepted methods using traditional methods such as X-ray structural analysis, optical, electron-rustal, and atomic force microscopy (AFM), IR and EPR spectroscopy.

The optimal kardan transmission according to the design solution and the materials used must operate satisfactorily throughout the entire service life specified in the technical specifications. It must have a torsional strength that ensures the transmission of torque without destroying the structure. In universal joints, bearings have a specific arrangement, in which the torque is transmitted at given speeds and angles under the influence of various operating factors. Slice connections of the shaft as a means of axial compensation of displacements provide a given transmission response to the movement conditions of the vehicle or unit.

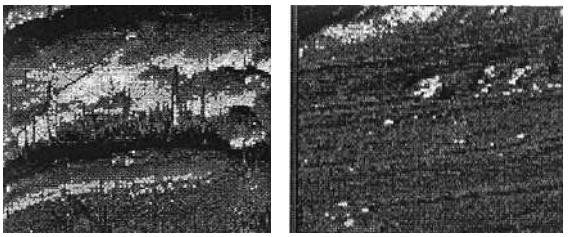
The dimensions of the crank gear must have the optimal proportionality to reduce the adverse effects of dynamic loads caused by inertial forces and vibrations.

Thus, the peculiarity of the driveshaft as a tribotechnical system is the need to systematically take into account all the diversity of operating factors when developing the optimal design with specified service life parameters.

The study of hinged joints and spline connections in the crank drives of various machines and mechanisms used in modern automotive and agricultural machinery has revealed their wear characteristics.

A significant portion of wear observed when fulfilling the requirements for the operation of cardan drives is corrosion-mechanical wear, which is characterized by a combination of operating factors inherent in this tribasystem: the presence of high contact stresses, a change in the sign of movement of individual parts of the structure, vibrations, strong loads, the influence of abrasive particles and corrosion-active external environments.

The friction surfaces of the spline joint have characteristic fatigue processes and are accompanied by abrasive and corrosive effects of the working medium (moisture, salt solutions, abrasive particles) (Fig. 3).



a **b**

Figure 3: The relief characteristic of the friction surface of the spline joint of the cardan shaft (×100): a - initial; b - after traveling 50 thousand km.

The composition of the lubricant used in the crankshaft construction differs qualitatively from the original lubricant in road conditions, containing abrasive particles (SiO_2), particles formed during the aging of contacting materials (iron, 60PP steel oxides), oxides and organic compounds, and particles of metal-containing organic compounds (Fig. 4).

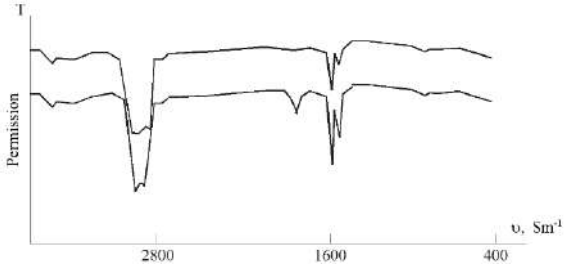


Figure 4: IR spectra of the I-20 lubricant after testing the initial (a) and friction pair St 60 PP - St 60 PP at a friction speed of 1 m/s and a specific load of 10 MPa (b). Trial time is 10 hours.

On the friction surfaces, the influence of abrasive particles and traces of plastic deformation of micro-roughness are clearly visible. This indicates the occurrence of a complex of physicochemical processes in the zone of friction action of the spline joint, leading to corrosion-mechanical wear of the tribojunction.

Wear of another crucial tribo connection of the crank gear - the universal joint - has a negative impact on the wear kinetics of the spline pair. The increase in clearance in the "bearing-crosshead ceiling" pair, leading to an increase in dynamic (impact) loads and fatigue processes in the spline connection, is the cause of such an indirect dependence. Aging of the spline connection (increase in clearance in the connection) leads to an increase in dynamic loads that accelerate the aging process in similar hinged joints.

Thus, when developing the design of a cardan transmission, it is necessary to consider the

combined impact of adverse tribotechnical phenomena in various connections of tribosystems.

Using the example of the St 60PP - St 60PP model system, we will consider the main tribotechnical phenomena in the friction contact zone of the spline connection of the cardan transmission.

The surface roughness parameters of the contacting bodies according to the indicator R_a=0.8...1.2 mcm and hardness HRC=42...45 units corresponded to similar indicators of real cardan transmissions used in the design of MAZ and KAMAZ type trucks.

To reduce axial forces in the movable spline connection, various thermal and physicochemical treatments are carried out. Phosphating - treating metal surfaces with an active composition of iron and manganese salts, as well as phosphoric acid - is one of the types of physicochemical treatment. As a result of the exposure of the phosphating composition to the metal sample surface, a layer of metal phosphates with specific characteristics such as porosity, hardness, ability to absorb and retain dry lubricants and lubricating oils is formed. In the literature, recommendations are given for the use of phosphate layers as an anti-wear agent in the spline connections of the crank shafts.

However, practical recommendations on the technology of applying phosphate layers for crankshaft parts are insufficient. Various compositions based on phosphoric acid or its salts are used for phosphating products made of ferrous and non-ferrous metals.

We used the standard preparation "Majef," which is widely used in applied mechanical engineering. The composition of the preparation is presented in Table 2. The results of preliminary experiments showed that the optimal composition of the modifying solution should be: 25-35 wt.% "Majev" salt and 65-75 wt.% water.

The technological regime for preparing experimental samples consists of the following. The suspension of the preparation was dissolved in water, the solution was boiled at 1.2-1.8 ks, settled, and cooled to 369-371 K. The metal samples were degreased with alcohol and acetone and placed in the working melt. The types of surfaces of experimental samples subjected to chemical-thermal treatment are shown in Fig. 5.

Microscopic analysis of the surface state of metal samples using the ASM method indicates the formation of a film in the metal consisting of a separate group of crystalline formations. With increasing processing time, the film duration increases, and the crystal sizes decrease.

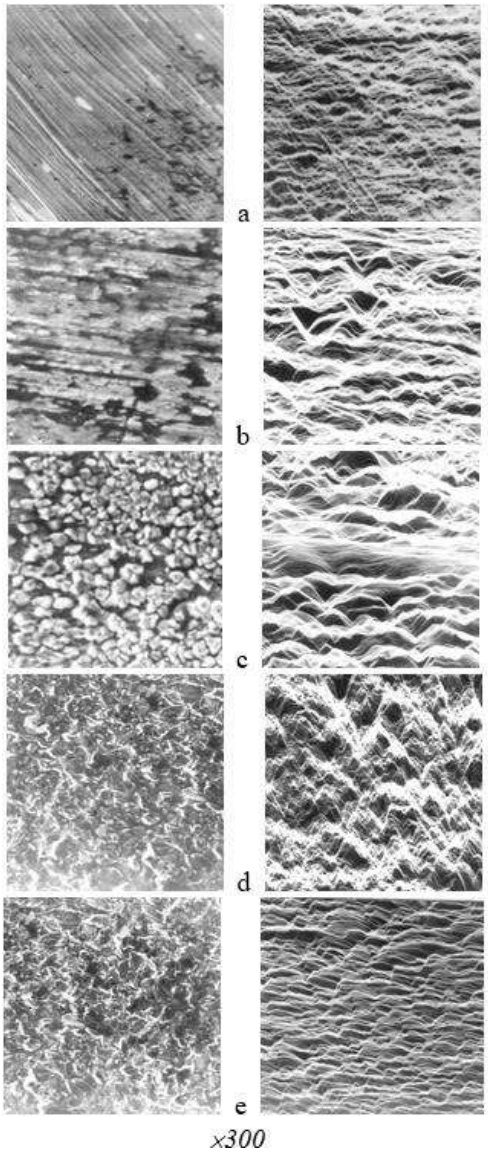


Figure 5: The surface of a metal roller made of steel 45: (a) initial and treated in a 30% aqueous solution of "Majef" for 0.03 Ks (b), 0.06 (c), 0.18 Ks (d) 0.42 (e).

The research results (Fig.6) indicate that phosphate films contribute to a decrease in aging intensity due to friction vapors and wedging loads on friction surfaces. However, it should be noted that over time, the phosphate film breaks down and exits the friction zone. After removing the phosphate film from the friction surface, its roughness significantly decreases, as the partial "solution" of microbarriers in individual micronoules fills the microcavities.

Table 2. Composition of the preparation "Majef".

Components	Composition, %
Ferrous general	0.3-3.0
Manganese, at least	14
Phosphates converted to P_2O_5	46-52
Sulfate ion	0.07
Calcium oxide, not more than	0.06
Water, no more than	19

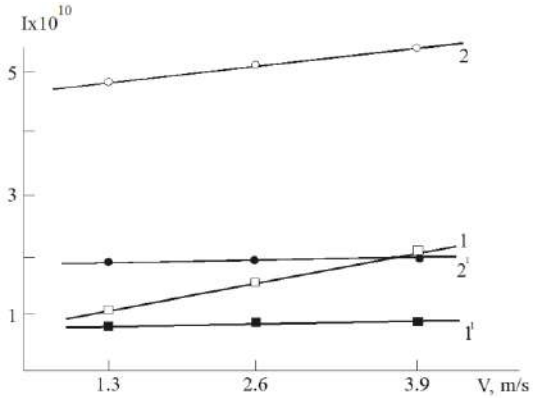


Figure 6: Dependence of the wear rate on the sliding speed in the friction pair 60 PP - 60 PP: initial (1 and 2), phosphatized 0.06 Ks (1' and 2') 0.5 MPa (1 and 1') and 1.0 MPa (2 and 2') under specific loads.

4 CONCLUSIONS

Technological phosphating regimes enable the formation of a film with a thickness of 10-25 μm. Modern designs of cardan shafts, manufactured using traditional equipment, can have total clearances of up to 0.1 mm (100 μm) in spline connections.

Therefore, phosphate coatings cannot fully compensate for errors in the technological process of manufacturing and assembling the spline connection of the cardan transmission and require additional processing to increase service life and operational efficiency. Phosphate coating is one of the options that can be used as a substrate for obtaining a composite coating that ensures the given operational life of the cardan transmission.

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