Magnetic lubricating oils based on organosilicon nanofluids

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Abstract The results of studying tribotechnical and physicochemical properties of various liquids have proved applicability of a dispersion medium, which is based on organosilicon liquids, for producing new-generation magnetic lubricating oils. The paper gives recommendations for choosing a dispersed magnetic phase. There is an original approach to selecting surfactants for stabilization of a magnetic oil colloidal structure, taking into account their dielectric properties and the effect on friction. The paper describes technological features of the synthesis of lubricating oils based on polyethylsiloxane PES-5 and chlorphenylsiloxane KhS-2-1VV containing nanosized magnetite. It also investigates lubricating properties of magnetic oils based on oligodiethylsiloxane and oligomethyl(chlorophenyl)siloxane under various friction conditions and shows their specific features. It analyzes the influence of various additives and fillers on tribotechnical characteristics of magnetic oils. It also defines a different mechanism of additives effects on frictional contact properties. The results of magnetic oil tests determine the most promising compositions for practical use in tribounits. Finally, there are recommendations on practical application of optimal compositions of magnetic lubricating oils in traditional and perspective tribounits with various operational parameters.

1. Introduction
Nowadays, traditional three-component magnetic liquids are well known, so their potential as a functional material is almost beyond its tether [1-3]. In order to lubricate tribocouplings that work continuously or for a short time at the boundary friction mode, it is necessary to create special magnetic liquids called magnetic lubricating oils with high lubricating properties and specific physicochemical characteristics created based on the system approach (viscosity, volatility, pour point and boiling point, etc.) [2, 3]. Moreover, antifriction and antiwear oil properties should be at the level of the best traditional lubricating oil properties [4, 5].

The main research objective was to develop the fundamentals of the magnetic lubricating oil technology based on siloxanes having high magnetic and tribological characteristics.

2. Selecting components for magnetic lubricating oils
Based on the requirements to magnetic oils for friction units, a dispersion medium (carrier liquid or substrate), which reaches 80 vol%, should have the following characteristics: low volatility, optimal viscosity-temperature properties, good lubricating properties at boundary lubrication, high resistance to oxidation when there is a finely dispersed magnetite, magnetic and rheological stability, low cost. It was established [6] that magnetic oil lubricating properties correlate well with the similar properties of the dispersion medium at a qualitative level.

According to physical properties, some brands of organosilicon liquids meet these requirements most fully. We studied lubrication capacity of the main groups of organosilicon fluids:
oligodimethylsiloxanes (PMS-100), oligodiethylsiloxanes (PES-5), oligomethylthienylsiloxanes (FM-6), oligomethyl(chlorophenyl)siloxanes (KhS-2-1BB), oligomethyleneilthienylsiloxanes (PMTS-5), oligomethylfluorosiloxane (FS-56). All these liquids are able to work in a wide range of temperatures, have low volatility and do not cause corrosion of structural materials.

We studied lubricating properties of organosilicon liquids and magnetic oils at high contact pressures using a three-ball friction machine MTSh-M [6]. To hold magnetic oil on a friction track, cylindrical magnets were placed between the balls in the mandrel so as they were facing the counter sample plane with the polar surface. An inhomogeneous field collected and held the magnetic oil near the magnet pole. The experiments included using ball samples with an 8 mm diameter and a cylindrical counter sample made of SH-15 steel. A sliding speed in the tests was 0.24 m/s and the initial contact pressure was 1.25 GPa.

Tribotechnical tests of organosilicon liquids and magnetic oils in the range of medium pressures were carried out according to the disk-finger friction scheme on a MTP friction machine [6]. The following oil properties were obtained at a sliding speed of 0.32 m/s and a contact pressure of 4.2 MPa. Materials of the friction pair are steel ST3 and bronze BrOTsS5-5.5. The amount of magnetic oil of 1-3 cm³ required for the test was applied to a disk. Under the influence of magnetic forces, oil was held as a half of the torus on the friction track.

Based on the analysis of physical and chemical properties, as well as friction tests, synthetic organosilicon liquids PES-5 and KhS-2-1BB are chosen as a basis of magnetic lubricating oils. They have low volatility, good rheological characteristics at low temperatures and high lubricating properties over a wide load range.

The synthesis of magnetic oils mainly involves using highly dispersed magnetite. It is obtained by a well-studied method of chemical condensation. Magnetite particles have a typical size from 5 to 17 nm with an average size of about 10 nm; the saturation magnetization of the particles is about 430 kA/m; microhardness of magnetite particles is about 5 GPa.

The stabilization of colloidal particles requires surfactants that are adsorbed on the magnetite surface and prevent the agglomeration of magnetic particles. They also provide sedimentation stability of a colloid in gravitational and magnetic fields. When obtaining magnetic lubricating oils, in order to stabilize a magnetic colloid, there is a number of additional requirements to a surfactant stabilizer. First, the surfactant dissolved in the dispersion medium of magnetic oils should not have a negative effect on oil lubricating properties. Second, the adsorption shells on particles should be resistant to thermomechanical effects in a tribocontact zone.

The use of a dielectric criterion parameter \( E \) notably simplifies the choice of a surfactant stabilizer. The criterion parameter \( E \) shows the relative difference in the permittivities of the components: \( E = \frac{|\varepsilon_p - \varepsilon_t|}{\varepsilon_p} \), where \( \varepsilon_t \) is a surfactant permittivity, \( \varepsilon_p \) is a base permittivity. According to this criterion, a dispersion medium permittivity should be slightly different from the similar characteristic of a surfactant stabilizer. Otherwise, the desorption processes of surfactant molecules from magnetic particles cause quality degradation of protective adsorption layers, so that colloidal stability deteriorates. In practice, it is impossible to make the final choice of a surfactant stabilizer without an experimental analysis of the experimental colloids stability.

Traditionally [7], oleic acid is used to stabilize organosilicon magnetic liquids and oils based on PES-5 and containing disperse magnetite. The obtained magnetic oils have good colloidal stability and saturation magnetization up to 30 kA/m.

Therefore, when a lubricant is a magnetic oil based on PES-5, then it is necessary to eliminate the content of a fatty acid dissolved in the dispersion medium by technological methods. Otherwise, even less than 1% of a free oleic acid in a magnetic oil based on PES-5 leads to wear increase by a factor of 1.5–2 due to the demonstration of the internal Rehbinde effect and the corrosive destruction of surfaces (Table 1, properties of PES-5 and PES-5 solution with an oleic acid (OA)). A disadvantage of fatty acids is also their strong screening of the surface, which reduces the effect of other additives.

Chlorophenylsiloxane KhS-2-1BV is good for stabilizing magnetic oils based on PES-5 with magnetic nanoparticles of carbonyl iron. Chemical adsorption of KhS-2-1BB liquid molecules occurred directly
during the synthesis of magnetic particles at a temperature of 200 °C on their catalytically active surface. The KhS-2-1BB stabilizer dissolved in the PES-5 carrier medium has a positive impact on tribological properties of a lubricant composition (table 1), so the friction process becomes smoother, the friction coefficient and wear are reduced throughout the load range.

We have obtained experimental batches of magnetic lubricating oils based on PES-5. In order to increase the thermal stability and reduce the low-temperature liquid viscosity in these oils, a stabilizer is organosilicon trimethylsilylated ethyl silicates with up to 20 % of residual hydroxyl and ethoxyl groups with silicon (oligomers MKS-2-0). The MKS-2-0 oligomer dissolves well in a magnetic oil carrier liquid. Due to surface-active ethoxyl groups, it is actively adsorbed on magnetite and friction surfaces. However, this oligomer can not properly modify the friction surface. Therefore, its effect on wear at high loads is insignificant (Table 1). The MKS-2-0 oligomer shows only weak antifriction properties in friction.

Table 1. Lubricating properties of dispersion media solutions with surfactant stabilizers (P is contact pressure, V is a sliding speed, f is a friction coefficient, I is linear wear intensity, d is a wear spot diameter).

| Lubricating composition | Frictional testing machine MTP (P = 4.2 MPa, V = 0.32 m/s) | Frictional testing machine MTSh-M (P = 1.25 GPa, V = 0.24 m/s) |
|-------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
|                         | f       | I, 10^-9       | f      | d, mm |
| 1. PES-5                | 0.12    | 9.0            | 0.21   | 0.69 |
| 2. PES-5+5 wt. % OA    | 0.13    | 20.0           | 0.32   | 0.89 |
| 3. PES-5+1 wt. % KhS-2-1VV | 0.10   | 4.5            | 0.13   | 0.42 |
| 4. PES-5+1 wt. % KS-2-0 |        |                | 0.15   | 0.53 |
| 5. KhS-2-1VV            | 0.06    | 0.5            | 0.18   | 0.68 |
| 6. KhS-2-1VV+1 wt. % ODBA | 0.11   | 0.56           | 0.19   | 0.68 |
| 7. KhS-2-1VV+1 wt. % MKS-2-0 | 0      |                | 0.15   | 0.62 |
| 8. KhS-2-1VV+1 wt. % 3N2TE | 0.05   | 0.41           | 0.12   | 0.32 |
| 9. KhS-2-1VV+1 wt. % MKhS | 0.10   | 0.48           | 0.16   | 0.59 |

A surface active compound ODBA (a class of amines) can find a limited application in obtaining magnetic oils based on KhS-2-1BB. A small concentration of ODBA in the carrier medium is indifferently reflected on friction and wear (Table 1).

In order to increase the temperature-time stability of siloxane magnetic lubricating oils, it was proposed to stabilize magnetic particles by a surfactant, which was synthesized by chemical grafting of active (carboxylic) groups onto dispersion medium molecules.

Synthesis of a surfactant-siloxane MKhS (modified oligochlorosiloxane) was carried out by grafting surface-active fragments of hydrocarbon polymers onto the polysiloxane skeleton. The oligochlorosiloxane KhS-2-1VV was the basis for grafting. This ensures the maximum affinity of a solvate shell on the surface of dispersed particles and dispersion medium. An acrylic acid is a modifying agent as acid groups have the greatest dispersing force and form a chemisorption bond with magnetite.

In order to improve lubricating properties of magnetic oils, we introduced special antifriction, antiwear and extreme pressure additives into their composition. The content of additives varied from 1 to 20 wt. %.

The following additives were dissolved in magnetic lubricant compositions based on PES-5 and KhS-2-1VV: DF-11, Sovol and 3N2TE. Additive DF-11 is a 50 % solution of zinc dialkylthiophosphate in oil. It is obtained based on isobutyl alcohol and 2-ethylhexanol. It improves antioxidant, anticorrosive and antiwear properties of lubricating oils. Sovol is a mixture of penta- and tetra-chlorodiphenyls containing 40% chlorine. It is used as an antiwear and extreme pressure additive. The additive stabilizer
3N2TE contains the chlorinated ether of pentadiene and improves anti-wear and extreme pressure properties of oils. Table 2 shows the lubricating properties of dispersion media solutions with additives.

The additive-stabilizer 3N2TE improves lubricating properties of dispersive media most effectively due to forming protective films with metal chlorides on the friction surface. Regardless of the siloxane dispersion medium composition, the Sovol additive reduces friction and wear well at moderate contact pressures (Table 2). The DF-11 additive is effective only when dissolved in the organosilicon liquid KhS-2-1BB.

### Table 2. The influence of additives on dispersion medium lubricating properties.

| Lubricating composition | Frictional testing machine MTP \((P = 4.2 \text{MPa}, \ V = 0.32 \text{m/s})\) | Frictional testing machine MTSh-M \((P = 1.25 \text{GPA}, \ V = 0.24 \text{m/s})\) |
|-------------------------|---------------------------------|---------------------------------|
|                         | \(f\) | \(h_0,10^9\) | \(f\) | \(d, \text{mm}\) |
| 1. PES-5                | 0.12  | 9.0         | 0.21  | 0.69           |
| 2. PES-5+5 wt. % 3N2TE | 0.14  | 3.7         | 0.14  | 0.26           |
| 3. PES-5+5 wt. % DF-11 | 0.13  | 4.1         | 0.17  | 0.45           |
| 4. PES-5+5 wt. % Sovol | 0.11  | 3.4         | 0.16  | 0.62           |
| 5. KhS-2-1VV            | 0.06  | 0.5         | 0.18  | 0.68           |
| 6. KhS-2-1VV+5 wt. % Sovol | 0.05 | 0.39       | 0.12  | 0.72           |
| 7. KhS-2-1VV+5 wt. % DF-11 | 0.07 | 1.4        | 0.15  | 0.43           |

### 3. Oil synthesis technologies

The basic technology for synthesis of magnetic oils includes several stages [7]. First of all, a highly dispersed magnetite is obtained from the condensation reaction proposed by Elmore.

After washing magnetite from salts and ammonia to \(\text{pH} = 7\), there is its peptizing with a surfactant solution in a hydrocarbon solvent and removing of water. Then a mixed solvent consisting of a siloxane and a low-viscosity volatile hydrocarbon is added to the mixture. Here the volume ratio of hydrocarbon to the silicone fluid volume should be 1:2. A decrease in the amount of hydrocarbon triggers a decrease in the magnetite concentration in the final product. The final suspension is stirred at a temperature of 50 \(^\circ\text{C}\) for 2–3 h, after peptization the water residues and low-boiling components are removed in the vacuum.

At the final stage, additives are added to the magnetic fluid at a temperature of 40–50\(^\circ\text{C}\) and thorough mixing to obtain the oil. A necessary condition for this is a good compatibility of an additive with the dispersed medium, as well as a sufficiently high affinity of the surfactant additive with a hydrocarbon part of a surfactant stabilizer. It can be explained. Experimental studies of additive content lubricating properties show that they are effective only at a high concentration (15–20 wt. %). At the same time, a composition of a dispersion medium changes significantly, which can affect colloidal stability of magnetic oils and other functional properties.

To eliminate the disadvantages of monofunctional surfactants, which are used in the synthesis of magnetic oils, we studied the possibility of stabilizing magnetic nanoscale particles using the 3N2TE additive, originally designed to reduce friction and wear (Table 2). The adsorption capacity of this surfactant is shown due to the presence of a carbonyl group in molecules. It was assumed that a sufficiently long hydrocarbon radical provides the steric factor of protecting particles from agglomeration.

The chlorosiloxane KhS-2-1VV was used as a dispersion medium. To simplify the adsorption of the 3N2TE surfactant, magnetite was washed from the water by acetone. Peptization lasted in siloxane at a temperature of 100 \(^\circ\text{C}\) for 90 h. There was a noticeable dispersant effect of the 3N2TE surfactant on colloidal magnetite. After peptization and removal of water traces, we obtained a magnetic oil with the...
following properties: 15–30 kA/m saturation magnetization, 0.3÷0.6 Pa·s viscosity depending on the selected component ratio.

Another magnetic oil based on KhS-2.1VV and stabilized by a specially synthesized surfactant siloxane (MKhS) was obtained as follows. Magnetite, which was washed from the water by acetone, was treated by a surfactant solution with an acid number of about 60 in oligochlorosiloxane (15–20 %). The surfactant content was 35 wt. % of the magnetite weight. Peptization was carried out at 80 °C in vacuum. It was noted that the synthesized surfactant had a high dispersant effect. After separation in a centrifuge we have obtained a magnetic oil with a saturation magnetization of ≈25 kA/m and a viscosity of about 0.45 Pa·s. An oil with the magnetization of up to 40 kA/m can be obtained by changing the component ratios, however at the same time the viscosity increases from 0.4 to 0.6 Pa·s. A magnetic oil is resistant to thermal effects up to 180÷200 °C. The advantage of the proposed scheme for obtaining a magnetic oil is the high affinity of a surfactant and a dispersion medium. It is especially important for producing a stable colloid with a flat viscous temperature dependence.

4. Experimental results
The magnetic oil MM1-PES (Table 3, a dispersed phase and a stabilizer are indicated in the brackets after an oil grade) is stabilized with an oleic acid (OK) and contains about 6 vol% of a magnetic phase. Oil viscosity is several times higher than the base viscosity, which can not be explained by the indicated volume content of a magnetite. Apparently, solvate shells of particles have a polymolecular structure. This fact causes a significant increase in a dispersed phase volume, and hence increase in viscosity. An important contribution to the real content of a dispersed phase is made by the surface layer of particles, which lost its ferrimagnetic properties due to chemical interaction with an oleic acid. MM1-PES oils saturation magnetization is not too high (19-25 kA/m), however it is enough for the oil to retain good magnet mobility in friction nodes.

MM1-PES magnetic oil has very good sedimentation and aggregative stability in gradient magnetic fields. The low volatility of its components makes it possible to use the oil in a gas medium and in vacuum environment at a temperature from -40°C to 100°C. Higher temperatures cause distraction of solvation shells in particles, moreover coagulation processes start to develop in the oil. If the temperature is below -40 °C, the oil loses its magnet mobility, so it stops reacting to an external magnetic field.

Tribotechnical properties of MM1-PES oil (Table 3) are insignificantly different from similar properties of PES-5 organosilicone fluid. To improve them, the authors used additives with different effects on friction processes.

There is an unusual dependence of lubricating properties on additive concentration. After addition to non-magnetic oils, usually there is a non-linear decrease in friction and wear. Here at low concentrations of Sovol additive (a mixture of penta- and tetra-chlorodiphenyl), oil lubricating properties deteriorated (Table 3). In fact, combination of SAA stabilizer and SAA additive caused a negative synergistic effect. The mechanism of this phenomenon is not completely clear, but it is definitely connected with the sorption processes of all SAA in the oil. Probably, after addition in oil, there is a gradual partial displacement of molecules of SAA stabilizer adsorbed on magnetic particles by more polar additive molecules. For this reason, in MM1-PES oil, oleic acid is released from the outer layer of a particle solvate shell, this negatively affects friction. When the additive content in an oil exceeds 6–7 wt%, friction and wear start to decrease due to domination of adsorbed additive molecules on contacting surfaces.

MM1-PES magnetic oil containing 15 wt% of Sovol additive has lubricating characteristics comparable with those of a good TM-5-18 gear oil. Further increase of additive concentration in the oil leads to decreasing friction and wear, however at the same time it triggers processes leading to destruction of an oil colloidal structure and increasing the corrosive effect of additive chlorine.

Table 3. The influence of additives on dispersion medium lubricating properties.
Adding DF-11 additive (zinc dialkyldithiophosphate in oil solution) to MM1-PES oil did not significantly increase its lubricating properties, although this additive worked well in hydrocarbon lubricant compositions. It is believed that when the temperature in the friction zone is about 200°C, the additive decomposes, and its active products form protective films on the surface consisting of metal sulfides and phosphides. Perhaps low efficiency of the additive is associated with insufficient heat generation in the friction zone or formation of a micellar (nematic phase) of the additive.

3N2TE additive (chlorinated ether of pentadiene) allows improving anti-wear properties of MM1-PES magnetic oil significantly. The significant effect in this case is achieved when an additive content is about 5 wt%. The friction process after addition becomes more uniform and the amplitude of friction force oscillations decreases sharply. This additive does not change oil colloidal stability noticeably.

MM2-PES and MM3-PES magnetic oils (the additive is oligomer MKS-2-0) differ from other oils on the same basis by high magnetization, which goes with relatively low viscosity in MM2-PES oil. MM2-PES oil contains plastic nanosized iron particles, their volume concentration is several times lower than in MM3-PES oil due to greater magnetization of iron than magnetite.

Lubricating properties of magnetic MM2-PES and MM3-PES oils are acceptable only at medium contact pressures. Oil efficiency at high contact pressures is low due to the lack of a sufficient number of molecules capable of chemical modifying the surface by their thermal destruction products. The results of MM2-PES oil tests showed that it is impossible to improve tribotechnical properties of magnetic oils by replacing the dispersed phase solid magnetite with soft iron.

The given data on the properties of various magnetic oils based on PES-5 show that the most promising oil for practical applications in tribounits is MM1-PES. It is recommended for various tribocouplings in order to reduce friction energy losses, component wear and increase a mechanical life.

Aside from magnetic characteristics, MM1-PES oil due to its rheological, low-temperature and colloidal properties closely corresponds to plastic lubricants with a polyethylsiloxane dispersion medium by evaporation and environmental immunity. OKB-122-7 lubricant is recognized among the greases containing polyethylsiloxane as one of the best in tribological properties. Lubricant tribotechnical properties are determined by the magnetic oil test procedure and shown in Table 3.
122-7(1) lubricant tests were carried out with a single filling of a friction unit with grease. OKB-122-7(2) lubricant tests were carried out with constant replacement of its losses on a friction track. Regardless of test conditions, MM1-PES magnetic oil lubricating properties are higher than those of OKB-122-7 lubricant even without an additive. An important result of this comparison of lubricants is that magnetic oils can be effectively used instead of greases containing polyethyilsloxane.

Table 4 presents lubricating properties of HS-2-1VV magnetic oils determined at various contact pressures with a magnetic field in the friction zone. It also shows their saturation magnetization and plastic viscosity. Oil saturation magnetization (22÷41 kA/m) is quite sufficient to supply oil to the friction zone by magnetic forces and keep it there. Plastic viscosity of chlorophenylsiloxane magnetic oils is one of the lowest for magnetic oils based on organosilicone fluids and, for example, 4-5 times less than polyethyilsloxane oil viscosity. The moderate oil viscosity makes it possible to use the abovementioned oils not only in tribounits operating in the boundary lubrication mode, but with hydrodynamic lubrication if the internal friction heat release does not disrupt normal operation of the unit. Based on the sizes of magnetic particles and oil viscosity, it can be assumed that they can be used in elastohydrodynamic friction modes, but there are no reliable data confirming or refuting such statement.

Studies have shown that magnetic oils based on HS-2-1VV oligomer might be used for lubrication when the environmental temperature is up to ~180 °C. Higher temperatures gradually break down protective shells of magnetic particles and disrupt colloidal stability. As for negative temperatures, these oils were tested at friction to ~30 °C and there were no irreversible changes in their colloidal structure. Apart from low volatility and wide operating temperature range, HS-2-1VV magnetic oils are characterized by chemical inertness, explosion safety and non-toxicity.

Table 4. Lubricating properties of magnetic oils based on HS-2-1VV.

| Lubricating composition | Oil saturation magnetization, kA/m | Plastic viscosity, Pa·s | Frictional testing machine |
|-------------------------|-----------------------------------|------------------------|---------------------------|
|                         |                                   |                        | MTP | MTSh-M |
|                         |                                   |                        | f |  \( I_b \times 10^9 \) | f |  d, mm |
| 1. HS-2-1VV             | -                                 | \( \approx 0.045 \)   | 0.03 |  0.5 |  0.21 - 0.15 | 0.68 |
| 2. MM1-HS (Fe3O4+MHS)   | 25                                | 0.4 - 0.6              | 0.15 |  0.6 |  0.16 |  0.51 |
| 3. MM1-HS +5 wt. % Sovol| 23                                | -                      | 0.09 |  0.55 |  0.15 |  0.47 |
| 4. MM1-HS +5 wt. % DF-11| -                                 | -                      | -   |  -   |  -   |  -   |
| 5. MM2-HS (Fe3O4+MK)    | 38                                | -                      | 0.12 |  5.3 |  0.17 |  0.63 |
| 6. MM3-HS (Fe3O4+ODBA)  | 41                                | -                      | 0.11 |  8.3 |  0.25 |  0.73 |
| 7. MM4-HS (Fe3O4+3N2TE) | 22                                | 0.3 - 0.6              | 0.10 |  0.95 |  0.13 |  0.35 |
| 8. TM-5-18              | -                                 | -                      | 0.07 |  0.4 |  0.15 |  0.35 |
| 9. VNII NP-274          | -                                 | -                      | 0.10 |  \( \approx 6.5 \) |  0.13 |  0.54 |

The highest lubricating properties belong to synthesized magnetic oils based on oligochlororganosiloxane MM1-HS (stabilized with modified chlorosiloxane MHS) and to oil MM4-HS (stabilized with chlorine-containing additive 3N2TE). These oils are able to maintain colloidal stability in gravitational and high-gradient magnetic fields for a long time.

Even without other additives MM1-HS and MM4-HS magnetic oils are good in reducing friction and wear in a steel-bronze coupling at medium loads (Table 4). In this range of loads, these lubricating oils
have similar lubricating properties as the non-magnetic TM-5-18 oil, but significantly exceed the plastic lubricant VNII NP-274. We do not take into account the fact that the movement of the developed magnetic oils in the friction unit can be controlled without contact using magnetic forces, so as to increase their lubricating action efficiency significantly.

At contact pressures typical of gears, MM4-HS oil shows abnormally high lubricating properties, the same as the transmission non-magnetic oil TM-5-18. This is due to the fact that 3N2TE molecules protect dispersed particles from agglomeration well. They also form low-shear iron chloride films on steel friction surfaces that protect against metal contact and reduce the adhesive wear component. A comparison of MM4-XC oil tribo properties and HS-2-1VV dispersion medium containing 3N2TE additive (Table 4) indicates that the additive as a stabilizer neutralized the negative effect of magnetite dispersed particle aggregates on abrasive destruction of surfaces.

It is enough to use 5 wt. % of Sovol and DF-11 additives to improve anti-wear properties of MM1-HS magnetic oil (unlike oils based on PES-5). Further increase in the additive content does not give a significant improvement of properties. The oil with DF-11 additive has shown good properties at high contact loads: the diameter of the wear spot on steel balls after addition has decreased by almost 50%. Perhaps this is due to the synergistic effect of joint modification of the friction surface by active chlorine atoms from the oil base, as well as sulfur and phosphorus from the additive.

Magnetic oils MM2-HS and MM3-HS, which are stabilized with organosilicon SAA (MK is an organosilicon compound, ODBA is a compound belonging to amines), have a high saturation magnetization, however their lubricating properties are ordinary, especially in MM3-HS oil. This is due to the fact that the stabilizer molecules can not chemically modify the friction surface and form a strong protective adsorption layer on it. In addition, oils are not stable enough. A dispersed medium is slowly separated from them at rest under the action of gravitational and magnetic fields.

5. Conclusions
Some organosilicon fluids are good as a dispersion medium for creating advanced magnetic lubricating oils with good lubricating properties, low volatility and a wide temperature range. We proposed and justified the choice of surfactants to preserve colloidal stability of magnetic oils under boundary friction conditions. Based on the results of tribotechnical tests, there was a preliminary selection of additives and fillers in order to improve lubricating properties of oils that are well compatible with a dispersion medium. Finally, the paper presents technological features of obtaining magnetic oils based on polyethylsiloxane PES-5 and chlorphenylsiloxane XC-2-1BB.

In general, it is reasonable to use organosilicone magnetic oils in essential tribounits, which were traditionally lubricated with plastic materials based on siloxanes. This will significantly increase the reliability and life of friction units. However, this will require some structural changes of these units in order to include special magnetic systems in their structure to preserve the reserve volume of magnetic oil and ensure its inflow to rubbing surfaces.

Thus, we have studied lubricating properties of magnetic organosilicone oils under different friction conditions and considered their specific features. We have also analyzed in detail how a number of antiwear additives dissolved in oils affect friction and proposed the mechanism of their action.

The main conclusion in the work is that according to tribological properties, the developed magnetic oils are not as good as liquid lubricants. However, they significantly better than the plastic greases on a silicone base. Along with this, taking into account the unique magnetic properties of the proposed magnetic oils that give them an advantage over non-magnetic oils, their effective application in various traditional and prospective tribunals is reasonable.

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