



Resistant Properties of Lubricating Materials with Fullerene Nanoadditives

**V.P. Oleksandrenko^{1*}, V.V. Yefymenko², N.G. Kalmykova², O.V. Efimenko², R.V. Budiak³,
Yu. M. Nelyubin¹**

¹*Khmelnytskyi National University, Ukraine*

²*National Aviation University, Ukraine*

³*Kalynivka Technological Applied College, Ukraine*

**E-mail:oleksandrenkovp@gmail.com*

Received: 22 April 2023; Revised: 14 May 2023; Accept: 30 May 2023

Abstract

The purpose of this article is to study the possibility of using fullerene additives and their effect on the antiwear properties of aviation mineral and synthetic oils. The method of increasing the anti-wear properties of mineral MK-8p and synthetic Mobil Jet Oil 254 oil for turbojet aircraft engines by adding fullerene additive C60 is considered. It has been shown that the anti-wear properties of synthetic Mobil Jet Oil 254 oil for turbojet aircraft engines exceed MK-8p mineral oil by more than 10%. Increasing the concentration of fullerene additive in oils increases the wear resistance of conjugated surfaces. It was established that the increase in the concentration of the fullerene additive in oils shifts the critical load to higher values for both mineral and synthetic oils. The intensity of this growth is observed in mineral oil to a greater extent than in synthetic oil. The use of fullerenes as an anti-wear additive to oils for turbojet engines is proposed, which improves anti-friction properties and reduces the wear of parts of machines and mechanisms. Scientific progress is determined mainly by experimental research, the conduct of which in this direction is quite relevant.

Key words: fullerene additives, mineral oil, synthetic oil, four-ball machine, wear rate, critical load.

Introduction

The main function of lubricating oils and greases is to reduce friction and wear of the surfaces of parts that rub. An important place in increasing the reliability of the equipment and increasing its service life is occupied by the wear resistance of the parts. During operation, intensive wear of friction nodes occurs as a result of significant loads, speeds and temperatures, exposure to aggressive environments and vibrations. One of the most economically beneficial ways to increase the durability of friction nodes in various machines and mechanisms is to improve the quality of lubricants, primarily their lubricating properties, which is achieved mainly by introducing anti-wear, anti-seize and anti-friction additives into them. The introduction of additives into oils and lubricants allows you to satisfy two main requirements of technology: increasing the service life (reliability) of machines and mechanisms; fuel energy conservation, because about 30 % of the energy produced in the industrialized countries of the world is ultimately wasted on friction. In recent years, one of the ways to improve the operational properties of materials is the use of nanomaterials - fullerene as additives to them, including as additives to lubricating materials. This is due to the fact that these compounds are unique objects from the point of view of electronic structure, physical and chemical properties. An extraordinary feature is also the fact that it is the only soluble form of carbon in hydrocarbon compounds, which allows it to be used in a variety of directions. Conducting experimental studies on the possibility of using fullerenes and fullerene-containing carbon black as anti-wear additives is a very relevant area of scientific work.

Analysis of the latest research



Information on the study of the tribological properties of fullerenes is very scarce and mainly concerns fullerene C60. Several works have been published where fullerene C60 was studied in the form of a solid film as a solid lubricating coating, therefore it was concluded that C60 is promising for solving various tribological problems [1]. As shown in works [2-5], quite significant progress has recently been made in obtaining and researching nano-objects, new nanomaterials and nanotechnologies have emerged. Nanoclusters of a number of metals, fullerenes and carbon nanotubes were synthesized. A step forward was made in the methods of observing and studying the properties of carbon nanostructures, connected with the development of physicochemical methods of studying their use in lubricating materials. Research has been conducted, based on which it is proposed to use fullerenes as an antioxidant additive, which significantly improves the thermo-oxidative stability of oils in comparison with traditional additives.

Fullerenes are characterized by high chemical inertness in relation to the process of monomolecular decay. Thus, the C60 molecule retains its thermal stability up to a temperature of over 1500 °C, which cannot be said about other antiwear and antioxidant additives. However, in the presence of oxygen, the oxidation of this form of carbon to CO and CO₂ is observed already at significantly lower temperatures (about 250 °C), but such a temperature is not reached in the lubrication system of modern automobile and aircraft engines, although in aviation supersonic aircraft when the engine is stopped, due to cessation of heat removal from the area of the turbine bearings, such an increase in temperature for a short period of time is possible [3].

The scientists performed a detailed quantitative study to determine the impact of fullerene additives on the performance characteristics of graphite-based lubricating compositions. The results of these studies can be used as a basis for the development of a "superlubricant" that will provide a coefficient of surface friction below 0.001.

As a lubricating base, highly oriented pyrolytic graphite (HOPG) was used, which, together with finely dispersed graphite powder of natural origin, was introduced into a mixture of concentrated sulfuric and nitric acids (in a volume ratio of 4:1) and stirred for 16 hours. The powder processed in this way was washed with water, dried at a temperature of 100°C, after which the sample was subjected to heat treatment for 15 seconds. This led to the formation of layered graphite particles, which were then introduced into a 70 % alcohol solution and subjected to ultrasonic treatment. Then, layered graphite particles together with C60 or C70 fullerene powder were sealed under vacuum in a quartz ampoule, which was kept at a temperature of 600 °C for 15 days. The graphite intercalated with fullerenes obtained as a result of the described procedure was used to obtain an anti-friction coating, which was a film with an area of 2.3x2.3 m² and a thickness of 0.2 mm.

Fullerene-containing carbon black and powdered fullerene C60 provide a noticeable improvement in the antifriction and antiwear properties of steel-steel and copper-steel friction pairs, especially in the area of high loads and contact pressures. The greatest improvement occurs in the steel-steel friction pair. For copper pairs, it was determined that the presence of fullerene C60 in pure form or in fullerene carbon black leads to the formation of a fullerene polymer film of considerable thickness on the friction surface, which plays a protective role [6-8].

The coefficient of friction of this film μ was measured by the standard method as the ratio of the friction force to the applied lateral load. As a result of the measurement, values of $\mu < 0.001$ were obtained, which is half as much as for the standard grease based on MoS₂ ($\mu \approx 0.002$) and for graphite grease ($\mu \approx 0.001$). As a physical mechanism that determines the characteristics of a lubricating film based on pyrolytic graphite intercalated with fullerenes, scientists consider the possibility of rolling of fullerene molecules on the graphite surface, which is characterized by much lower friction compared to the sliding of graphite surfaces relative to each other due to the higher contact area in the latter case. It follows that fullerenes act as micro-rolling bearings that reduce the coefficient of friction. [10,11]. The limits of application of fullerenes are very wide. As far as lubricants are concerned, many additives for lubricating oils and greases are being developed on the basis of fullerenes. Recently, the production of lubricants based on fullerenes, which are characterized by extraordinary characteristics, is promising.

Formulation of the problem

The main lubrication units in turbojet aircraft engines are rolling bearings, in contrast to the lubrication units of piston engines in which sliding friction prevails. The temperature of the outer cage of such bearings reaches 125-150 °C, which is mainly created due to the heat coming from the turbine impeller. After the engine stops, when the air blowing decreases, the heat flow coming from the impeller heats the bearing bracket and the oil that lubricates it and removes heat from the friction zone to a temperature of 200 °C.

In turbojet engines of supersonic aircraft, the temperature in the friction nodes increases sharply both due to the increase in the load on the turbine bearings and due to the heat coming from the combustion chamber and the turbine impeller. At the same time, the temperature of the oil rises. In promising supersonic turbojet engines, the temperature in the friction nodes can reach 400 and even 540 °C, and the oil temperature up to 150-200 °C. For operation at such temperatures, liquid mineral oils are unsuitable, and synthetic oils must contain anti-wear and antioxidant additives, which performed both its functions under such conditions. Therefore, research aimed at obtaining and using new additives for lubricating materials that would work at high temperatures and significant loads is quite relevant.

Purpose and tasks

The purpose of the work was to study the possibilities of using and introducing new, promising complex additives to fuel and lubricant materials that will work for a longer period of time than traditional additives.

To improve the operational properties of fuels and lubricants - thermal oxidation stability of hydrocarbons, anti-wear characteristics, phenolic antioxidant additives - "ionol", anti-wear additives - "Hatec-580" are used, but at elevated temperatures they quickly oxidize. Therefore, the main task of this scientific work is the introduction of new, promising complex additives to fuel and lubricants based on nano-sized carbon materials (fullerenes), which are more resistant to the oxidation process, and the study of changes in the antiwear properties of lubricating materials under their influence.

To achieve the goal, the following tasks were solved:

- determination of tribological parameters of mineral MK-8 π and synthetic Mobil Jet Oil 254 turbojet aircraft engine oils with C60 fullerene content on a standardized four-ball friction machine;
- studying the possibility and expediency of using fullerene additives in aviation mineral and synthetic oils.

Research materials and methodology

The development and introduction into operation of new lubricating oils with the aim of expanding the raw material base for their production and improving operational properties was carried out simultaneously with the development of engine construction. The large transmitted power of aviation gearboxes, in combination with their small weight and dimensions, leads to increased operating conditions of friction pairs, an increase in thermal and dynamic stress of engine parts and assemblies. Gears of reducers, as mentioned above, work under conditions of high contact loads. The strength of the films of low-viscosity aviation oils suitable for lubricating the supports of turbojet engines under these conditions is insufficient. To ensure reliable lubrication of the gears of the gearbox, oils with a higher viscosity and higher lubricating capacity are required.

Contradictions in the quality requirements of mineral oils, which must combine high lubricity with satisfactory viscosity-temperature characteristics to ensure reliable engine start-up at low temperatures, have led to the need to use a mixture of low-viscosity mineral oils for the lubrication of helicopter propeller gearboxes and turboprop engines (type "MK-8") with highly viscous residual oils "MC-20" (or "MK-22"). Moreover, the ratio of the indicated oils in the mixtures is different for different types of engines. An alternative solution to this contradiction is the use of Mobil Jet Oil 254 synthetic oil in the engine and gear system of Airbus Helicopters H-145 helicopters. Mobil Jet Oil 254 is an extremely high performance synthetic oil for third generation gas turbine engines, developed to meet their requirements and use in commercial and military aviation. This product is made from a specially formulated synthetic ester base oil and is enriched with an additive package. The oil has excellent thermal and oxidative stability, resisting degradation and scale formation while maintaining the physical characteristics required by manufacturer and military specifications. The physical properties of Mobil Jet Oil 254 are similar to the previous generation gas turbine lubricants currently available. The effective working range of the oil is from minus 40 °C to plus 230-250 °C. The viscosity of synthetic oils at temperatures of 250-300 °C is higher than that of mineral oils of equal viscosity at 100 °C, they have better thermal stability, low evaporation and low tendency to high-temperature deposits and foaming. Synthetic oils are superior to mineral oils in terms of antioxidant properties, and have equal or better anti-wear and anti-scratch properties. In this regard, their service life is several times longer than the service life of mineral oils. Recently, effective antifriction additives (friction modifiers) have been introduced into synthetic oils, which contribute to improving their performance in the high temperature zone and antiwear properties.

New synthetic materials, the operational characteristics of which are significantly superior to natural ones, are the basis of humanity's advancement along the path of progress. Fullerene is essentially a new form of carbon. The C60 molecule contains fragments with fivefold symmetry, which are not found in nature for inorganic compounds (Fig. 1). Therefore, it should be recognized that a fullerene molecule is an organic molecule, and a crystal formed by such molecules (fullerite) is a molecular crystal that is a connecting link between an organic and an inorganic substance. Each carbon atom in the C60 molecule is located at the vertices of two hexagons and one pentagon and does not fundamentally differ from other carbon atoms.

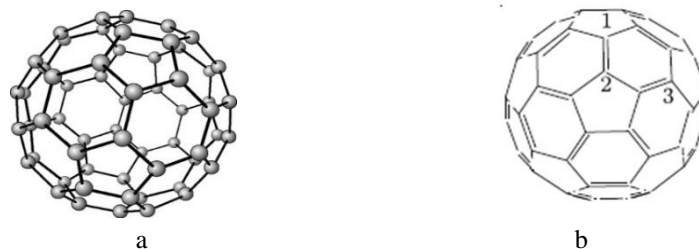


Fig. 1. C60 fullerene molecule: a – general view; b – double bonds between carbon atoms

The carbon atoms that make up the sphere are bound together by a strong covalent bond. The thickness of the spherical shell is 0.1 nm, the radius of the C₆₀ molecule is 0.357 nm. The length of the C – C bond in the pentagon is 0.143 nm, in the hexagon - 0.139 nm.

The C₆₀ fullerene molecule maintains its thermal stability up to 1700 K, which is significantly higher than the temperature in the friction unit of the rolling bearing of the gas turbine of the helicopter engine or in its gearbox.

However, in the presence of oxygen, the oxidation of this form of carbon to CO and CO₂ is observed already at significantly lower temperatures (about 500 K). The process leads to the formation of an amorphous structure in which there are twelve oxygen atoms per C₆₀ molecule, while the fullerene molecule almost completely loses its shape. When the temperature is further increased to 700 K, the intensive formation of CO and CO₂ and the final destruction of the ordered structures of fullerenes occur.

Of interest is the halogenation of fullerene, especially its fluorination. In the first works devoted to fullerene fluorides, the reaction of its interaction with gaseous fluorine was used, as a result of which a mixture of products was formed. The solubility of C₆₀ fullerene itself in non-aromatic solvents is low, while its fluorides are quite soluble in hexane, chloroform, and acetone, and with aromatic compounds they form stable crystal solvates under normal conditions.

The research was conducted using MK-8 mineral aviation oil and Mobil Jet Oil 254 synthetic oil with additives of different fullerene content. Control of the content and solubility of C₆₀ fullerene in oils was determined according to the method described in [9]. The investigated fullerene additives in different mass ratios of finely dispersed powder were added to the oil and mechanically mixed to a homogeneous suspension.

The quality of hydrocarbon lubricants is determined by their viscosity and anti-wear properties in the working temperature range. From a chemical point of view, these properties are provided, first of all, by the molecular weight and degree of branching of hydrocarbon chains. One of the main operational properties of oils is high resistance to oxidation and anti-wear properties.

To assess the effect of fullerene on the antiwear properties of oils, tribological tests were performed on a standardized four-ball friction machine in accordance with GOST 9490 (ASTM D2783) (Fig. 2).

According to the results of the research, wear was determined, which was estimated by the diameter of the wear spots d and the critical load P_k of the transition to seizure.

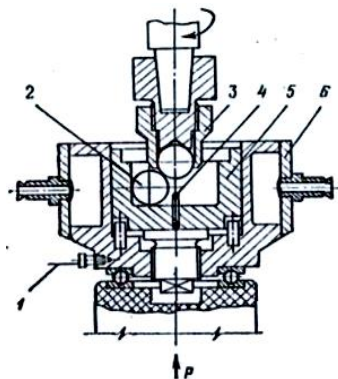


Fig. 2. Four-ball friction machine: 1 – screw; 2 – balls; 3 – friction node; 4 – acoustic probe; 5 – glass; 6 – housing

The three lower balls are fixed immovably in the cup of the machine with the lubricant being tested. The upper ball, which is fixed in the spindle of the machine, rotates relative to the three lower ones under a given load with a rotation frequency of 1460 ± 70 rotate/m. Turning the balls during the test is not allowed.

Balls must be made of bearing steel ShKh-15 not lower than the II degree of accuracy, class B, with a diameter of 16 or 20 mm. It is possible to use balls from new real bearings for testing.

Antiwear properties on a four-ball friction machine are determined for oils and plastic lubricants used to lubricate friction surfaces.

The method consists in testing the lubricating material on a friction machine under specified axial loads and determining the main tribological characteristics of lubricating materials: bearing capacity - according to the critical load P_k , anti-seize properties according to the burr index - I_b , ultimate load capacity - according to the welding load P_z and anti-wear properties - according to diameter of wear spots (d).

Before starting the test of each sample of lubricant, all parts of the machine with which the lubricant comes into contact during the test (the cup with the parts of attachment of the lower balls and the parts of attachment of the upper ball) are washed with gasoline or benzene and dried in air. The balls used in the test are also washed with gasoline and air-dried.

Testing of each lubricating material is carried out at the temperatures established in the regulatory and technical documentation.

The test consists of a series of determinations. Each determination is carried out on a new sample of the tested lubricant with four new balls.

To conduct the test, the balls are fixed in the spindle of the machine and the cup for the lubricating material. When testing the oil, it is poured so that the balls are completely covered with it. Then a cup with lubricating

material is installed in the machine, the load is set and the electric motor is turned on. In order to avoid deformation of the balls, it is necessary to avoid shock loads.

When conducting a test at elevated temperatures, the electric heater is previously turned on. After reaching the set temperature, create the necessary load and turn on the electric motor. The test temperature must be maintained with an error of no more than $\pm 5^{\circ}\text{C}$.

The duration of the test from the moment of switching on to the moment of switching off the electric motor when determining the critical load, welding load and burr index should be 10 ± 0.2 s, when determining the wear rate - 60 ± 0.5 min.

When determining the critical load, which characterizes the ability of the lubricating material to prevent the occurrence of burr on the friction surfaces, a series of successive tests with a decrease or increase of the load are first carried out in accordance with a number of loads given in the test standard. Two parallel tests are conducted.

When welding, it is necessary to turn off the electric motor immediately to avoid damage to the machine.

The wear index, which characterizes the influence of the lubricant on the wear of the friction surfaces, is determined under the constant load established in the regulatory and technical documentation for the lubricant. Two parallel tests are conducted. After the end of the test and cooling of the friction assembly below 40°C , drain the oil and wipe the balls with gasoline or alcohol.

Then measure the diameters of the wear spots of each of the three lower balls in the direction of sliding and perpendicular to it in a plane perpendicular to the axis of the microscope objective with an accuracy of 0.01 mm (Fig. 3).. The result of the measurement is taken as the average arithmetic value of the measurements of the wear spots of the lower balls in two directions.

The results of solving the main tasks of the problem and their discussion

The object of research of this work is the process of influence of nano-sized carbon materials (fullerene C_{60}) on anti-wear properties of mineral MK-8p and synthetic Mobil Jet Oil 254 oils of turbojet aircraft engines.

The subject of the study is the main tribological characteristics of aviation oils with additives of fullerene nano-sized carbon materials, determined according to the standard method on a four-ball friction machine.

The resource and reliability of engines largely depends on the extent to which the used aviation oil meets the operational requirements of its use. After the discovery of fullerenes, it became possible to create new lubricating materials. This possibility was indicated both by the ideal spherical shape of C_{60} fullerene molecules and by the base of these molecules (carbon), which in the form of graphite has long been widely used as an antifriction component of a whole class of lubricating materials. Numerous experiments conducted recently indicate increased lubricating characteristics of oils as a result of adding a small amount of fullerenes to them.

A characteristic feature of modern jet aircraft engines is the absence of sliding bearings. Rolling bearings are used as supports for the engine rotor shaft and aggregate drive shafts. The coefficient of rolling friction is in the range of 0.001-0.003 for ball bearings and 0.002-0.005 for roller bearings, while for sliding bearings this value is ten times greater (approximately 0.01). The rotors of modern aircraft engines are well balanced and, despite their high rotation speeds and considerable weight, the maximum radial load on the bearing does not exceed 1500 N. Anti-wear properties were studied using a four-ball friction machine according to ASTM D2783 according to the parameters of wear spot diameter (d) and critical load (P_k). The last indicator characterizes the maximum amount of load, at which metal contact (burrs) does not yet occur when rubbing standardized metal balls. When determining the limit wear indicator (d), the duration of the test from the moment of switching on to the moment of switching off the engine is 60 ± 0.5 min, under a standard load of 20 kg (196 N) and room temperature. In general, for each lubricating material, the test conditions are indicated in the regulatory and technical documentation. In this case, the same test conditions were chosen for mineral and synthetic oils for the convenience of comparing their properties.

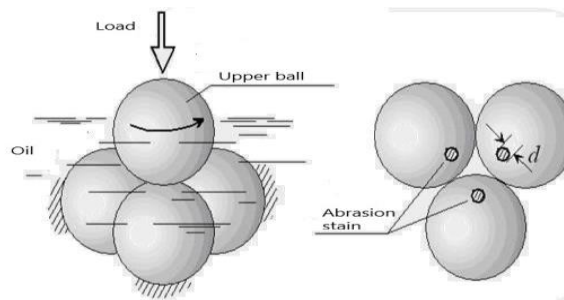


Fig. 3. Friction node

The dependence of the diameter of the wear spot on the concentration of the fullerene additive in mineral MK-8p and synthetic Mobil Jet Oil 254 aviation oils is shown in Fig. 4. As the research results showed, the increase in the concentration of the fullerene additive in oils does not significantly affect the amount of wear, although there

is a tendency to decrease the diameter of the wear spot. It should also be noted that a more intensive reduction in wear is observed in mineral oil than in synthetic oil. The nature of this action of fullerene-containing additives has not yet been completely clarified.

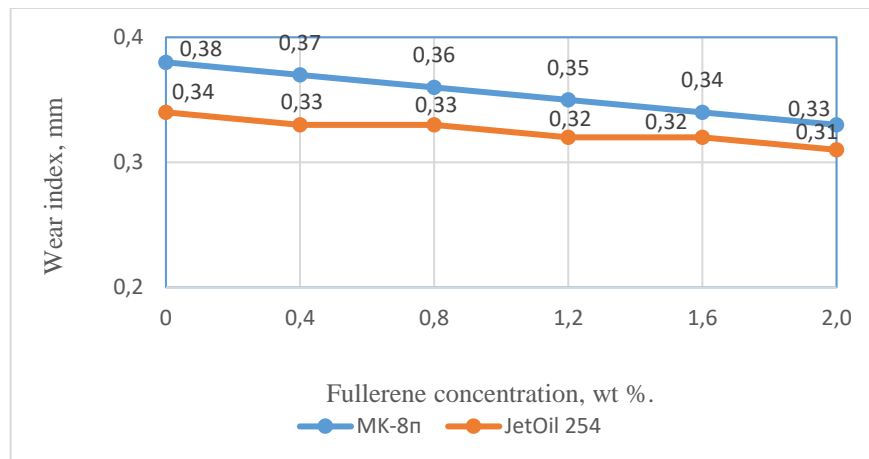


Fig. 4. Dependence of the wear index on the content of C60 fullerene in the oil

The critical load (P_k , kgf) is considered to be the load at which the average diameter of the wear spots of the lower balls is within the values of the limit wear value for this load, given in the ASTM D2783 table, the increase of which by the value of the next load in a series of loads causes an increase in the average diameter of the spots wear greater than 0.1 mm. The smaller value of the critical load from the two obtained values (Table 1 and Table 2) is accepted as the result of the test.

Table 1

Determination of critical load (P_k) for MK-8 oil

Load, kgf	Load, N	The average diameter of the wear spots of the lower balls, mm	Critical load, kgf
20	196	0.38	-
40	392	0.46	-
60	588	0.49	-
80	784	0.53	-
100	980	0.57	-
120	1176	0.61	-
160	1568	0.65	-
200	1960	0.82	(P_k) 200

Table 2

Determination of critical load (P_k) for Mobil Jet Oil 254

Load, kgf	Load, N	The average diameter of the wear spots of the lower balls, mm	Critical load, kgf
20	196	0.36	-
40	392	0.41	-
60	588	0.45	-
80	784	0.51	-
100	980	0.54	-
120	1176	0.59	-
160	1568	0.61	-
200	1960	0.65	-
240	2352	0.68	-
280	2744	0.71	-
320	3136	0.89	P_k (320)
360	3528	0.96	+

The critical load characterizes the beginning of the destruction of the lubricating film and the transition from a normal type of friction to an abnormal one, which is characterized by large wear of parts. From the above

tables, it can be seen that the critical load for mineral oil MK-8 under the same test conditions is 1960 N, while for synthetic oil Mobil Jet Oil 254, the critical load is 3136 N. This can be explained by the fact that synthetic oil contains a package of additives that significantly improve its anti-wear properties, while mineral oil contains only one antioxidant additive.

The dependence of the critical load on the content of the fullerene additive in oils is shown in Fig. 5.

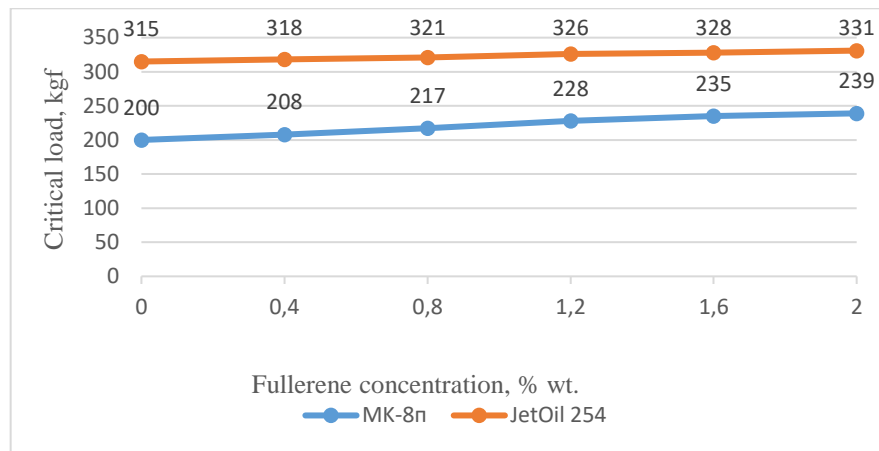


Fig. 5. Dependence of the critical load on the content of fullerene in the oil

Research results have shown that increasing the concentration of fullerene additives in oils shifts the critical load to higher values, both for mineral and synthetic oils. It should also be noted that the intensity of this growth in mineral oil is observed to a greater extent than in synthetic oil, possibly due to the effect of the additive package.

Based on the totality of the obtained results, it is possible to predict and predict the mechanism of antifriction and antiwear action of fullerenes as follows. In the process of tribopolymerization of mineral oil, a coating is formed on the friction surfaces in the form of a three-dimensional tribopolymer network connected to the substrate by chemical bonds.

This coating protects the rubbing surfaces from direct contact, and at the same time, being a spatial polymer mesh, retains the mineral oil, thus providing both a low-wear mode of friction and a low coefficient of friction. This process can occur without the presence of C60. However, without fullerene, the formation of a tribometallopolymer coating probably requires more time and more specific conditions. Due to its high reactivity, the presence of fullerene dramatically accelerates the tribopolymerization process and leads to the formation of a tribopolymer network, in the nodes of which there are mainly C60 molecules. This fundamentally changes the pattern of friction, as the tribopolymer protective coating in this case is implemented much faster and the low-wear and anti-friction mode of friction has time to be implemented before the destruction of the protective film. Finally, if in the process of friction the tribopolymer coating is disturbed (for example, under the influence of increased load) and there is a direct contact of the friction bodies, the process of tribopolymerization increases and the tribofilm is restored.

Therefore, tribocontact is a rather powerful reactor for various kinds of structural transformations, and one can expect the appearance in the friction zone of those fullerene modifications that have increased hardness and can determine the properties of surface films formed in the process of tribowear.

Conclusions

Fullerene nanoadditives are an effective means of increasing the tribological properties of oils of both mineral and synthetic origin. It was established that an increase in the concentration of the fullerene additive in oils up to 2% by weight. contributes to the growth of anti-wear properties of mineral oil MK-8p by 15%, synthetic oil Mobil Jet Oil 254 by 10%.

It was found that an increase in the concentration of the fullerene additive in oils shifts the critical load to higher values. At a content of 2% wt. fullerene critical load increases for mineral oil MK-8p by 19.5%, and for synthetic oil Mobil Jet Oil 254 by 5%.

A more positive effect of C60 fullerene additives on the tribological properties of mineral oil compared to synthetic oil was established: according to the indicator of the wear spot diameter - 1.5 times, according to the critical load indicator - 3.9 times, which is related to the difference in the oil base and the presence in a synthetic oil package of complex additives.

It was found that the anti-wear properties of synthetic oil Mobil Jet Oil 254 for turbojet aircraft engines exceed the indicator of MK-8p mineral oil by more than 10%, and the critical load - by 58%.

Scientific progress in this direction is mainly determined by experimental studies, the conduct of which is quite relevant.

References

1. Dmytrychenko N.F., Mnatsakanov R.G., Mikosyanchyk O.A., Kush A.I. Kinetics of wear of contact surfaces with the use of C60 fullerene additive to engine oil // *Journal of Friction and Wear*. - 2009, 30 (6), pp. 399-403.
2. Kuskova N.I. Tribological characteristics of nanocarbon materials. *Electronic processing of materials*, Mykolaiv, 2006, No. 6, pp. 50-56.
3. Valerii Yefymenko. Oxidative stability of lubricating materials with fullerene nanoadditives/ Valerii Yefymenko, Tetiana Kravchuk, Oleksandr Yefimenko// – K.: Вісник НАУ, №1, 2021. – P. 57 - 62. <https://doi.org/10.18372/2306-1472.86.15445>
4. Polunkin E.V., Kameneva T.M., Zhyla R.S. Peculiarities of the antioxidant action of exomodified fullerenes C60 at the oxidation of organic compounds // *The International research and practice conference “NANOTECHNOLOGY AND NANOMATERIALS (NANO-2017)”*, 23-26 August 2017, Chernivtsi. - P. 778.
5. Pat. 23255 Ukraine, IPC C 10 N 10/00. Kovtun G.O., Pluzhnikov V.O., Zhila R.S. etc. Fullerene C60 - antioxidant additive to lubricating oils. Publ. 10.05.2007.
6. Mykhaylenko O. V. Fullerenes, nanotubes and nanorings: – stereochemistry and method of coding (nomenclature). Complexes of fullerenes with calixarenes. Diss. Ph.D. chemical Sciences, Kyiv. - 2005. - 137 p.
7. Vicens J. Calixarenes in the Nanoworld / J. Vicens, J. Harrowfield. - Dordrecht: Springer, 2007. - 395 p.
8. Kovtun G.A. Fullerene C60 in the breakdown of oxidation chains of organic compounds / G.A. Kovtun, T.M. Kameneva, R.O. Kochkanyan // *Catalysis and petroleum chemistry*. – 2003. – No. 11. - C. 36-38.
9. Yefimenko V.V., Yefimenko O.V., Kalmykova N.G. Control and determination of the concentration of fullerene additives in hydrocarbon liquids // XV International Scientific and Technical. conf. "Avia-2021", April 20-21, 2021. theses add. - K.: NAU, 2021. - P.19.10-19.13. // <http://conference.nau.edu.ua/index.php/AVIA/AVIA2021/paper/view/8308/6860>.
10. Podcherniaeva I. A., Yurechko D. V., Panashenko V. M. Some development trends in the development of wear-resistant functional coatings // *Powder metallurgy and metal ceramics*. - 2013. - T. 52. - no. 3-4. - WITH . 176-188.
11. Achanta, S., Selis, J.P. (2007). MEMS/NEMS nanotribology. In: Gnecco, E., Meyer, E. (eds.) *Fundamentals of Friction and Wear. Nanoscience and technology*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-36807-6_23

Олександренко В.П., Єфіменко В.В., Калмикова Н.Г., Єфіменко О.В., Будяк Р.В., Нелюбін Ю.М. Протизносні властивості змащувальних матеріалів з фулереновими наноприсадками

Метою даної статті є дослідження можливості застосування фулеренових присадок та їх впливу на протизносні властивості авіаційних мінеральних та синтетичних олив. Розглянуто метод підвищення протизносних властивостей мінеральної МК-8п та синтетичної Mobil Jet Oil 254 олив для турбореактивних авіаційних двигунів шляхом добавки фулеренової присадки C_{60} . Показано, що протизносні властивості синтетичної Mobil Jet Oil 254 оливи для турбореактивних авіаційних двигунів перевищують понад 10 % мінеральну оливу МК-8п. Збільшення концентрації фулеренової присадки в оливах підвищує зносостійкість спряжених поверхонь. Встановлено, що зростання концентрації фулеренової присадки в оливах зміщує критичне навантаження в область більш високих значень як для мінеральної, так і для синтетичної оливи. Інтенсивність цього зростання в мінеральній оливі спостерігається в більшій мірі, ніж у синтетичній оливі.

Запропоновано використання фулеренів в якості протизносної присадки до олив для турбореактивних двигунів, що поліпшує антифрикційні властивості та зменшує знос деталей машин і механізмів. Науковий прогрес визначається в основному експериментальними дослідженнями, проведення яких в даному напрямку є досить актуальними.

Ключові слова: фулеренові присадки, мінеральна олива, синтетична олива, чотирьохкулькова машина тертя, показник зносу, критичне навантаження.