TRIBOLOGICAL RESEARCH OF THE CHROME- GRAY CAST IRON COUPLING WITH LUBRICATION IN DIFFERENT ENVIRONMENTS
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CERCETĂRI TRIBOLOGICE ALE CUPLEI CROM-FONTA CENUȘIE CU LUBRIFIERE ÎN DIFERITE MEDII

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ABSTRACT
In the given article, the results of the tribological research of the chrome-gray cast iron coupling are presented, the friction conditions between the cylinder liner and the compression segment being lubricated in various environments are modeled: diesel (control), pure biodiesel B100 and biodiesel-diesel B20 mixture. It was established that the average values of the coefficient of friction in the chrome-gray cast iron coupling, in the case of using biofuels B20, B100 as the lubricating material, are higher in relation to diesel fuel: by 15.6% for B20 and, respectively, by 23.3% for B100. The values of the total wear of the tribological coupling decreased, in relation to diesel, by 36.8% in the case of lubrication with B20 and by 39.5% - with B100.

REZUMAT
În articolul dat sunt prezentate rezultatele cercetărilor tribologice ale cuplei crom-fonta cenușie, fiind modelate condițiile de frecare dintre cămașa cilindrului și segmentul de compresiune cu lubrifiere în variate medii: motorină (martor), biodiesel pur B100 și amestec biodiesel-motorină B20. S-a stabilit că, valorile medii ale coeficientului de frecare în cupla crom-fonta cenușie, în cazul utilizării biocombustibililor B20, B100 în calitate de materialul lubrifiant, sunt mai înalte în raport cu motorina: cu 15,6% pentru B20 și, respectiv, cu 23,3% pentru B100. Valorile uzurii totale ale cuplei tribologice s-au micșorat, în raport cu motorină, cu 36,8% în cazul lubrifierii cu B20 și cu 39,5% - cu B100.

INTRODUCTION
At present, human society is faced with a variety of problems, the solution of which is imperative. According to the studies of established specialists (*FAO, 2016; Neupane D., et al., 2022; Bojariu R., et al., 2021; Tayari S., et al., 2020; Sun S., and Li K., 2020; Cerempei V., 2016; Schumacher L. G., 1996*), solving these problems requires a series of stringent measures:

- Ensuring food and energy security in the conditions of increased population growth in global society, degradation of soil fertility and depletion of deposits of fossil energy resources;
- Improving the ecological situation that bears the increasing negative impact of global warming caused by the increase in the concentration of greenhouse gases (GHG) in the Earth's atmosphere.

In connection with the exacerbation of the energy and climate crisis, it has become imperative for scientists and manufacturers to resort to the search and assimilation of new types of alternative fuels from renewable energy sources. To this category of fuels belongs the biofuel obtained from vegetable oils and from the residues of the food industry, called biodiesel, which ensures the conservation of GHG greenhouse gases and meets the economic requirements (hourly G_h consumption and specific g_e of fuel in small quantities), ecological and the exploitation techniques of compression ignition engines (CI engines). Biodiesel, or fatty acid methyl ester (FAME), is a liquid biofuel composed of mono-alkyl esters derived from animal or vegetable fats, which is obtained through the transesterification reaction. At the same time, biodiesel possesses the physico-chemical and exploitation properties, which are similar to those of diesel fuel, which allows it to be used in its pure state or mixed with diesel fuel in the combustion chamber, without essential changes in compression ignition engines (*Atabani A. E., et al., 2012; Knothe G., 2017*).

Due to its properties, biodiesel is produced and used to fuel motor vehicles at a constantly increasing rate (*Priya Deora P. S., et al., 2022; Vasiliev I. P., 2009; Dugin G. S., 2010*), being considered as a real alternative for petroleum fuels in different regions of the world – in Europe, on the American continent, in the countries of Southeast Asia (*Benea B. C., 2014; Cheremisinov P. N., 2019; Peterson C. L., et al., 1995*).

The advantages and prospects of biofuel production, as well as evidence of compliance with environmental protection requirements have been demonstrated by the results of multi-year use of biodiesel in different countries of the world (*Esmaeili H. A, 2022; Okoye P. U., et al., 2020; Sun S., and Li K., 2020; Smolinicov M. V., 2020; Geambașu S., 2018; Benea B. C., 2014; Corkwell K. C., et al., 2003; Hăbășescu I. et al., 2009*). According to the estimates of specialists in the field of compression ignition engines (*Jeswani H. K., 2020; Corsini A., et al., 2015; Burnete N., Naghiu A., Marișiu F., et al., 2008*), alcohol esters from vegetable oils appear to be the most promising alternative to fossil fuels.

The analysis of the situation in the field of biodiesel uses for fueling compression ignition engines demonstrates that the existing sources of information (*Hăbășescu I., Cerempei V., et al., 2008; Beșleagă I., 2011; Geambașu S., 2018; Benea B. C., 2014; Markov V. A., et al., 2015; Grekhov L. V., et al., 2015*) contain data on the physico-chemical and exploitation properties of esters (density, kinematic viscosity, cetane number, ignition temperatures, cloudiness, freezing, lower calorific value), the values of which are suitable for combustion in CI engines. Also in the above-mentioned sources, based on production tests, the general information is specified regarding the fact that fueling the engine with biodiesel ensures the reliability of its assemblies at the same level in relation to diesel.

Australian researchers (*Kalam Azad et al., 2019*) studied the tribological characteristics (coefficient of friction *COF*, wear and lubrication stability) on a four-ball tribotester using the ASTM D4172 standard in the environment of ultra-low sulfur diesel and of mixed eco-fuel B20 (20% biodiesel - 80% diesel). Each type of fuel/lubricant was studied for 3600 seconds (1 hour) after break-in and transition periods, the values of the friction coefficient at the end of the steady state friction period were with the lubrication in the diesel medium *COF*=0.09, and in the medium B20- *COF*=0.04. It is necessary to specify that the tribometer with four balls is used to study highly stressed couplings with risks of seizure, the resistance of the lubricant to high pressure being appreciated. In the tribometer with four balls, class I friction torques are used, their interaction occurs, theoretically, at a point with the following parameters: rotation speed - V=0.2-0.5 m/s, load - F≤8 kN, hardness surfaces - 62 HRC.

In internal combustion engines, including CI engines, the chrome-gray cast iron coupling in the compression segment piston-cylinder liner joint largely determines the reliability and durability of their operation. The mentioned coupling belongs to class III, the interaction of the elements occurring at the level of curved, cylindrical surfaces, with alternating movements. Therefore, the friction conditions in the four-ball tribotester do not effectively model the operation of the coupling in the piston ring-cylinder liner joint.

It should be noted that the fuels used in internal combustion engines, including in compression ignition (CI) engines, must have the ability to lubricate the contact surfaces of the movable joints of the parts of the engine equipment. This capacity is important, because it allows the reduction of frictional forces and reduces the wear of the joint surfaces of the tribological couplings: piston segment-cylinder liner, plunger-cylinder, injector-injector. It is known that diesel is obtained from crude oil by refining/distillation, being a mixture of C_nH_m aromatic, naphthenic and paraffinic hydrocarbons, containing from 12 to 20 carbon atoms in the molecules (*Kartashevich A. N., et al., 2014*). Diesel loses its lubricating capacity when sulfur compounds are removed from it (*Glushchenko A. A., 2019*). At the same time, biodiesel is a liquid synthetic fuel that is obtained through the chemical reactions of esterification and transesterification from natural triglycerides (vegetable oils, animal fats), the final product being a methyl ester of fatty acids. The results of previous research demonstrate that biodiesel, unlike diesel, does not require the use of active chemical additives for the proper functioning of the engine, which serve to reduce the probability of calamine deposition on the joined surfaces, of seizure of these surfaces, etc.

Diesel and biodiesel, having different origins and chemical compositions, respectively, demonstrate heterogeneous physicochemical properties (density, viscosity, surface tension of a drop of liquid, etc.). In these circumstances, it is of scientific and practical interest to research the behavior of an important tribological coupling from the CI engines endowment in the environment of diesel (control) and experimental biofuels: pure biodiesel B100, biodiesel-diesel mixtures. From the above-mentioned joints, in our view, the most complex and significant is the one formed by the compression segment and the cylinder liner, because they work at high temperatures (up to 600°C), with alternating loads and being subjected to the corrosive action of the products of burning. Therefore, *the purpose of our research* is to ensure the high values of the reliability and durability of the operation of the CI engine fueled with biofuel by determining the tribological characteristics of the compression segment-cylinder liner joint when they operate in the environment of diesel, biodiesel-diesel mixture, biodiesel.

MATERIALS AND METHODS

Based on the formulated goal, the following **specific objective** of the research was put forward: measuring the values of the coefficient of friction ***f*** between the chromed surface of the body and that of the gray cast iron GCI counterbody, as well as the wear ***U*** of these surfaces with lubrication in the diesel environment (control) and of biofuels (experiment): pure biodiesel B100, mixture B20 (20% vol. biodiesel-80% vol. diesel).

Tribological research was carried out in the specialized laboratory of the Technical University of Moldova on the MVPD-1KPI installation (Fig. 1) according to the method proposed by recognized specialists in the field of tribology (*Azhder V.V. et al., 1988; Croitoru D.M. et al., 1992*). The modeling of the actual operating conditions of the cylinder liner-piston segments coupling was obtained on a reciprocating friction machine with the frequency of n=3 double strokes/sec (180 double strokes/min) according to the scheme represented in figure 2, a. The body investigated (Fig. 2, b) was made in the form of a rectangular parallelepiped from steel 20 GOST 1050-2013 (2C22, EN 10083-2:2006), and the counterbody - from gray cast iron GCI 21 GOST 1412-85; (220, BS 1452:1990) (Fig. 2, c). The width of the side of the counter body, which was in contact with the chrome surface of the body, was 2 mm, while the area of the contact surface in the friction clutch was 20 mm^2.

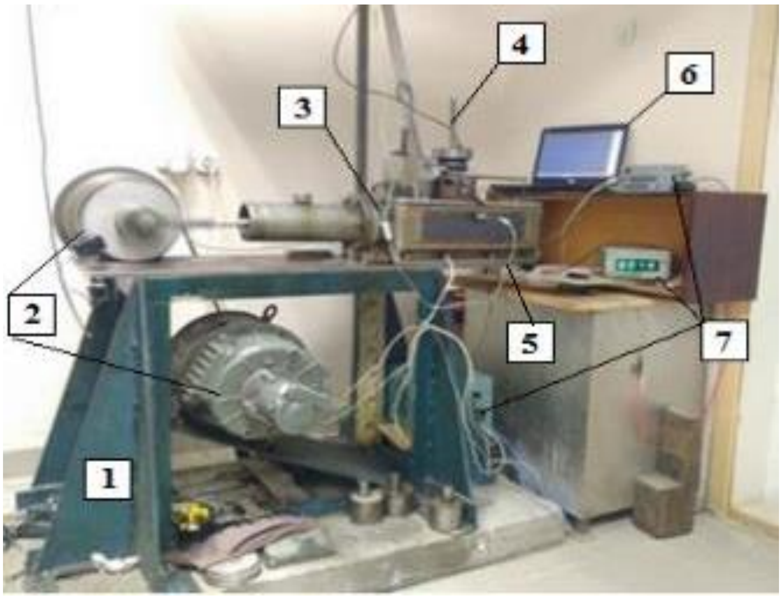
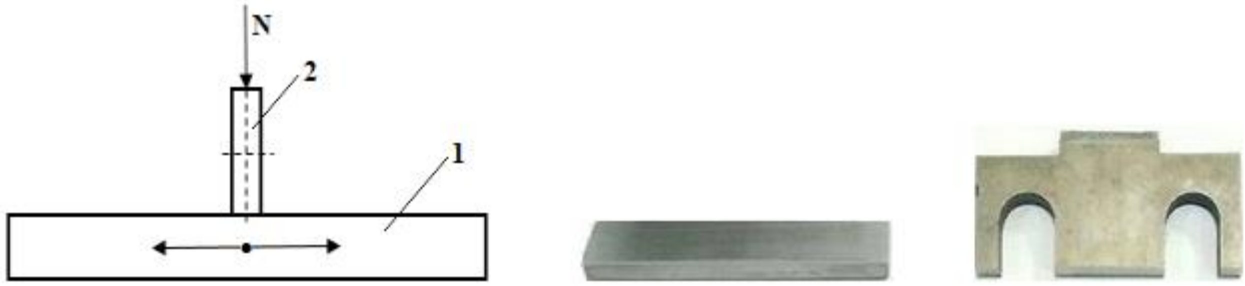


Fig. 1 - Tribological coupling research facility:
1 - frame; 2 - drive unit; 3 - tribological coupling test device with alternative movement;
4 - load loading device; 5 – fuel dosing device; 6 - computer;
7 - block of the electronic software complex

The working surface of the body was covered by the galvanic method with a layer of chrome, having a thickness of 0.1 mm. The contacted surfaces of the body and counterbody had after grinding the roughness R_a=0.20±0.02μm, which is indicated for the working surfaces of the cylinder liner and piston rings. Compliance with the above-mentioned conditions allowed the effective modeling of the operating conditions in the CI engines of the compression segment-cylinder liner coupling to be carried out within the tribological research. The choice of the compression segment for tribological research is argued by the fact that it supports thermo-dynamic loads with the highest values of the entire set of segments.

A drive assembly 2 (Fig. 1) is mounted on the frame 1 of the tribological coupling research facility, which includes the electric motor, the belt drive and the connecting rod-crank mechanism. From the above-mentioned mechanism, the reciprocating movement is transmitted to a tribological coupling testing device 3, where the coupling elements are installed: body and counterbody. Device 4 performs the constant load loading of the tribological coupling elements. The lubricant (researched fuel) is dosed by the device 5. The body with the chrome surface, which imitates the operation of the piston ring, was caught in a special device and performed the reciprocating movements, being driven by an electric motor.



a) b) c)

Fig. 2 - The tribological coupling elements researched

a) tribological coupling research scheme: 1- body, chromed surface; 2- counterbody, GCI
b) body with chrome surface; c) counterbody - gray cast iron

In the entire research process of the tribological coupling in the friction area, the fuel with which the CI engines were fed was dosed in regulated quantities: at stage one - pure diesel; at the second stage - B20 and at the third stage - B100. The load applied to the friction coupling had a value of 20 N. The supplied dose of fuel on the friction surface was one drop every 6 seconds, being provided with the help of a dropper. The duration of each research stage was 400.000 double runs (cycles), with the values of the tribological parameters (number of cycles, temperature in the friction zone, friction force) being recorded with the help of an electronic command and control system (ECCS) equipped with the friction machine. Body and counterbody mass check was done after every 50.000 double runs. The component parts of the ECCS are the respective sensors and transducers, an electronic block 7 (Fig.1), monitored by the corresponding software, with the processor at the base of the laptop 6, Dell Inspiron model. The tribological study was carried out at the ambient temperature t=20±2°C.

Before and after each research cycle of the tribological coupling, the tested samples (Fig. 2 b, c) were weighed using the VLA-200 analytical balance to determine their mass loss (wear). Preventively, before weighing, the body and counterbody were degreased with solutions of Nefras-C50/170 (GOST 8505-80) and sanitary alcohol C_2H_5OH (GOST 5962-2013). The measurement of the microhardness of the chrome surface was carried out according to GOST 9450-76 with the help of a PMT-3 device, the diagonal of the pyramid imprint in the researched material being measured, the applied force having the value of 1N. A diamond pyramid with a square base, having an angle between two opposite side faces of 136°, was used as the indenter. The microhardness value of the chrome surface was determined as the arithmetic mean of 9 measurements and was H_{μ}=13.44±1.28 GPa (1344±128 kgf/mm^2). The measurement of the surface roughness of the samples was carried out with the help of a profilograph-profilometer, SURTRONIC-25 model (manufacturer - Taylor Hobson, USA).

In order to verify the results obtained in the tribological research, bench research and tests were carried out under the exploitation conditions of compression ignition engines of the DC4 11.0/12.5 type (compression ratio ε=16), fueled with biofuel. It should be noted that agricultural tractors (Belarus brand) are equipped with DC4 11.0/12.5 engines, models D-240, D-241, D-243, which occupy about 52% of their total in agriculture in the Republic of Moldova. During the stand research, the D-241 engine was fueled with diesel (control) and experimental fuels: pure biodiesel B100 and small biofuels B20, B50. In the process of production tests, four D-243 engines were divided into two groups: a) control group (2 units), fueled with diesel fuel; b) the experimental group (2 units), fueled with B20 biofuel. Engine tests were carried out at the "Chetrosu" Didactic Experimental Station, Anenii Noi district, various agricultural works being carried out: preparing the soil before sowing, agricultural crops sowing, care operations for field and perennial crops (protection from diseases and pests, tillage between rows, administration of fertilizers, etc.), various transport works. The volume of work performed by each tractor varied between 647-724 engine-hours, which coincides with the average annual load of a Belarus 82.1 type tractor in the Republic of Moldova.

The assessment of the reliability and durability of the researched and tested engines was carried out based on the measurement of the values of the functional parameters that characterize the technical condition of the engines (engine oil pressure, gas flow rate in the engine crankcase, compression pressure, engine oil consumption during combustion, fuel injection pressure) and the properties of the engine oil in action. The pressures at the end of the compression in the cylinders of the D-241L engines were measured using a compressor (compressometer G-324D), and the oil pressure in the engine lubrication system - with the on-board equipment of the tractors.

Oil consumption during combustion was determined by measuring the volumetric amount of the portion of oil periodically added to the crankcase bath up to the level regulated by the engine manufacturing plant. The operational reliability of the tested engines was determined according to the recommendations of the interstate standard GOST 54783-2011.

The obtained values of the results of the experiments were processed with the application of the facilities of the STATGRAPHICS, MATLAB and Microsoft Office Excel programs.

RESULTS

The obtained values of the friction coefficient in the chrome-gray cast iron tribological coupling confirm the influence of the chemical composition of the lubricating material on the interaction process in the movable joint (Fig. 3). The average values of the coefficient of friction ***f***, in the case of using biofuels B20, B100 as the lubricating material, are higher in relation to diesel (***f***=0.03584): by 15.6% (***f***=0.04244) for B20 and by 23.3% (***f***=0.04675) for B100, respectively. The increase in the friction coefficient in the case of lubrication with the investigated biofuels probably occurred due to their higher viscosity values: B20 has viscosity μ = 4.43 mm^2/s (9.4% higher), B100 - μ = 8 mm^2/s (1.98 times higher), than that of diesel fuel - μ = 4.05 mm^2/s.

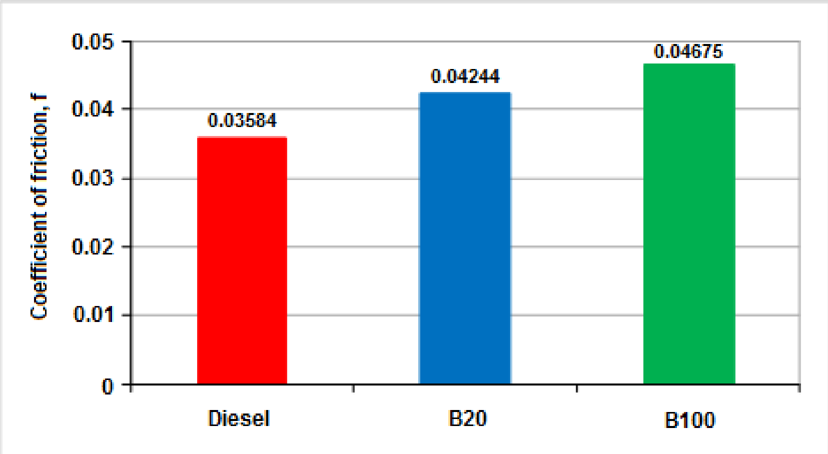


Fig. 3 - The average values of the friction coefficient of the tribological coupling depending on the lubricant used

It is important that at the temperature of the laboratory environment of 20±2°C, with the transition from diesel to B20 mixture and pure B100 biodiesel, the gradient of the increase of the friction coefficient ***f*** is lower than that of the volume fraction (% vol.) of biodiesel in the fuel mixture:

$$\frac{f_d - f_B}{f_d} < \frac{B}{100} \quad (1)$$

where:

f_B, f_d – values of friction coefficients in the biofuel and diesel environment, respectively;

B, %vol – volume fraction of biodiesel mixed with diesel.

As mentioned above, the researchers (*Kalam Azad, et al., 2019*) obtained the following values of the friction coefficient in the studies on a four-ball tribotester: in the diesel environment *COF* = 0.09, and in the B20- environment *COF*=0.04. The values obtained in our research on the car with alternating movements and with the same lubricants are lower for diesel (*COF*=0.036) and equal for B20 (*COF*=0.042). The difference in COF values can be explained by the differences in friction conditions and chemical composition, physico-chemical and exploitation properties of the investigated lubricants.

Our results regarding the values of the kinematic viscosity of diesel and biofuels at 20^0C coincide with the results of measurements at the same temperature, presented in the report of the Technical University of Cluj Napoca, 2010. In this report it is demonstrated that increasing the temperature has the effect of decreasing the viscosity of the studied fuels: at the temperature of 70°C the viscosity of diesel and B20M75E5 mixture (20% biodiesel, 75% diesel, 5% ethanol) was μ=1.7 mm^2/s, and that of pure biodiesel B100 decreased to 3.1 mm^2/s. The presented data allow us to assume that the further increase of the temperature in the tribological coupling up to 300-400°C, which happens in the combustion chamber of the engine, will have the consequence of equalizing the viscosities of the studied fuels: diesel, B20 mixture, pure B100 biodiesel. Under these conditions, the friction coefficient in the piston segment-cylinder liner joint can have equal values for the mentioned fuels.

The results of research on the dynamics of wear ***U*** for the elements of the tribological coupling (body - chromed surface and counterbody - cast iron GCI) with the variation of lubricants (diesel, biofuels B20, B100) demonstrate that the dependence of ***U*** values according to the number of cycles ***n*** (research duration ***τ***) obviously carries a rectilinear character (Fig.4). This finding is very important, because it indicates that the wear process in the performed experiments proceeded normally, without mechanical seizure. From the graph it can be seen that, after completing 400 thousand cycles, which is equivalent to 16 km, the wear values of the body – chrome surface, in the B20 biofuel mixture environment, increased by 0.1 mg (by 14.3%) in relation to diesel. At the same time, with the increase in biodiesel concentration up to 100% (B100), a decrease in ***U*** wear by 14.3% (by 0.1 mg) compared to B20 and equal to diesel wear is highlighted. Taking into account the fact that the tribological experiments are carried out under complex conditions and have a multifactorial character, wear being dependent on the physical-mechanical properties of the joined surfaces, the physical-chemical properties of the lubricating materials, the state of the environment, it can be found that, in cases of the use of different lubricants (diesel, B20, B100) the differences identified in the values of body wear with the chrome surface (Δ=±0.1mg) throughout the duration of the research are not large.

The wear values of the tribological coupling element, counterbody, from gray cast iron GCI, demonstrate that, after achieving 400 thousand friction cycles with the use of biofuels B20 and B100 as lubricants, the total wear of the counterbody (*U*≈1.7 mg) in both cases has lower values compared to wear in the diesel environment (*U*=3.1 mg) (Fig.4). The results of concrete measurements indicate that, in the case of using biofuels B20 and B100 for surface lubrication, the wear value *U* of the GCI counterbody decreased by 48.4% and 45.2%, respectively, in relation to the wear value of the diesel-lubricated counterbody.

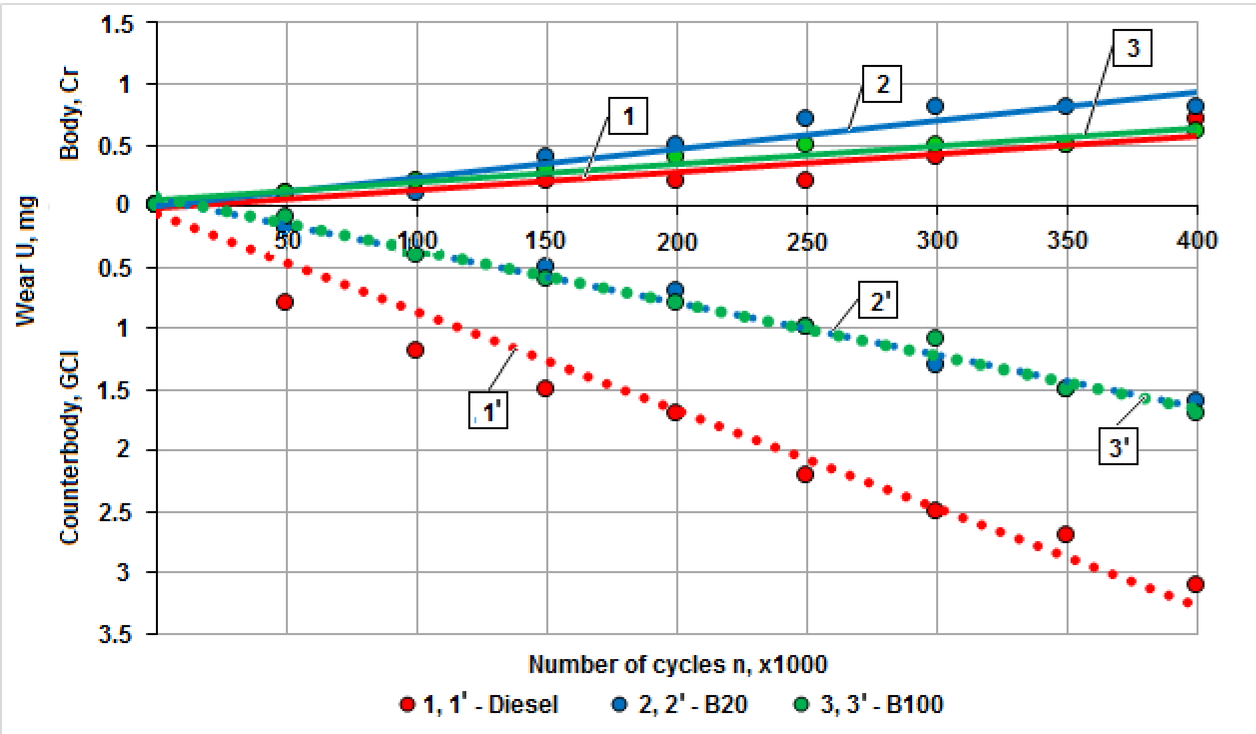


Fig. 4 - Dynamics of wear of tribological coupling elements with the use of different lubricants (diesel, biofuels B20, B100)

The character of the dynamics of the total wear $\boldsymbol{U_t}$ of the tribological coupling depending on the number of cycles ***n*** demonstrates that the exploitation of the tribological coupling with the use of biofuels B20 and B100 as lubricant ensures the lower values of the total wear $\boldsymbol{U_t}$ in relation to the case of lubrication in the diesel environment (Fig. 5). For example, in the friction process of the tribological coupling with the use of biofuels for lubrication, the total wear values $\boldsymbol{U_t}$ of the body - chrome surface and the counterbody - gray cast iron GCI, for the entire duration of the research, decreased by 36.8% for the B20 case ($\boldsymbol{U_t}$ *=2.4 mg*) and, respectively - by 39.5% for the case of B100 ($\boldsymbol{U_t}$*=2.3 mg*) in relation to lubrication in the diesel medium ($\boldsymbol{U_t}$*=3.8 mg*). The substantial decrease in total wear of the tribological coupling in the case of lubrication with B20, B100 biofuels is probably due to the chemical composition as well as the higher viscosity of the biodiesel, which overall improves the lubrication properties of the pure B100 biodiesel and the biodiesel-blend diesel B20.

It is important that mixing biodiesel with diesel in a ratio of 20:80 has a synergistic effect, because the value of total wear U_t of the tribological coupling elements with the use of B20 blend and pure B100 biodiesel as a lubricant does not differ much and is equal to U_t=*2.4 mg* and with U_t=*2.3 mg*, respectively.

So, the tribological research carried out demonstrated the veracity of our hypothesis regarding the positive impact of the lubricating material from biofuels (pure biodiesel B100 and biodiesel-diesel mixture B20) on the friction process in the tribological coupling chrome surface - gray cast iron. The given hypothesis was based on the results of studies of the physical-chemical and operational properties of the above-mentioned fuels.

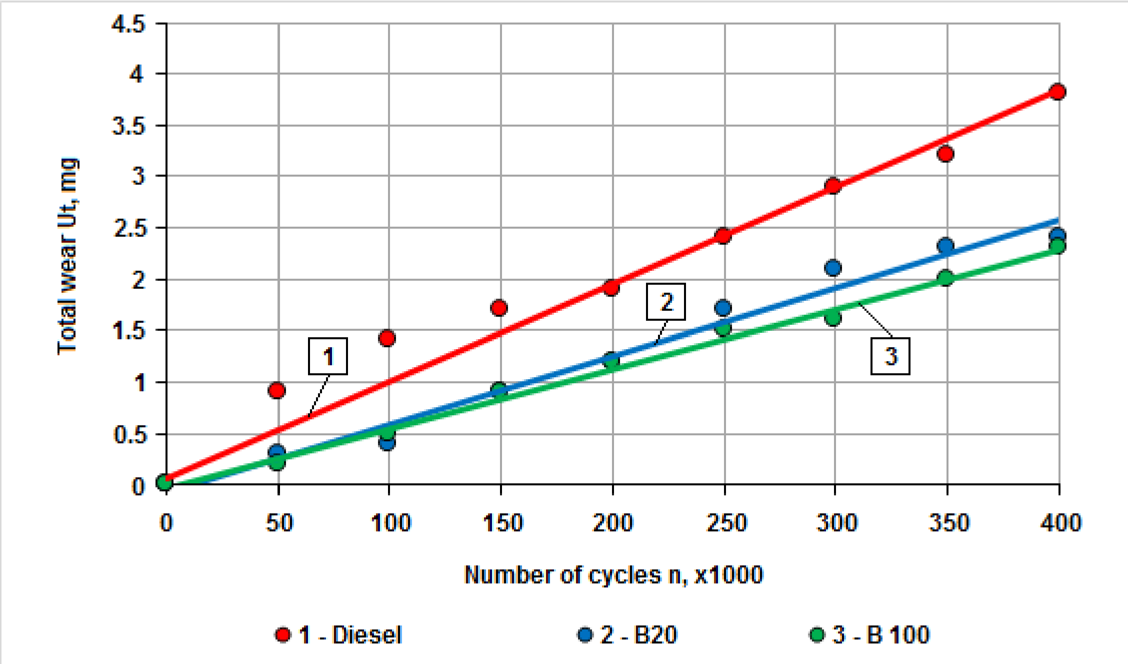


Fig. 5 - Dynamics of the total wear of the tribological coupling with the use of different lubricants (diesel, biofuels B20, B100)

The results of bench research of the D-241 engine and production trials of the D-243 engines confirm the positive impact of biofuels on the parameters of operational reliability and durability. The values of the functional parameters of the D-243 engines, subjected to tests under the conditions of agricultural production, being fed with diesel fuel and B20 mixture, indicate that the technical condition of the engines was stable and in accordance with the operating rules, submitted by the manufacturing plant in Minsk. The functional parameters that characterize the technical condition of the tested engines had the following values: coolant temperature - ≤85-90ºC, oil temperature in the engine crankcase bath - ≤ 75-82 ºC, engine oil pressure – 0.30-0.32 MPa, gas flow rate in the engine crankcase - 79-81 l/min, compression pressure – 19.5-21.3 MPa, engine oil consumption during combustion - 112...137 g/h, fuel injection pressure – 17.5-18.0 MPa. The physico-chemical and exploitation properties of the engine oil in action (kinematic viscosity, alkalinity, sulfated ash content) changed in the process of production trials equally in engines fueled with diesel and mixed biofuel B20.

CONCLUSIONS

1. It was established based on tribological research that the average values of the coefficient of friction in the chrome-gray cast iron coupling, in the case of using biofuels B20, B100 as the lubricating material, are higher in relation to diesel: by 15.6% for B20 and by 23.3% for B100, respectively.

The increase in the coefficient of friction in the environment of the investigated biofuels probably occurred due to the higher values of their viscosity.

2. The values of the total wear U_t of the tribological coupling for the entire duration of the research decreased, in relation to the lubrication in the diesel medium, by 36.8% for the B20 case and by 39.5% for the B100 case. The substantial decrease in total wear of the tribological coupling in the case of lubrication with B20, B100 biofuels is probably due to their chemical composition, as well as their higher viscosity, which overall improves the lubrication properties of B100, B20 biofuels.

3. The results of bench research and production trials confirm the positive impact of biofuels B20, B100 on the parameters of reliability and durability of operation of compression ignition engines.

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