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Effect of an electric field on friction of silicone rubber against steel in the motor base oil's environment

Juliusz B. Gajewski*, Marek J. Głogowski, Natalia Hałuszka

Wroclaw University of Science and Technology, Department of Cryogenic, Aeronautical and Process Engineering, Wybrzeże S. Wyspiańskiego 27, 50-370 Wrocław, Poland

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The paper presents the experimental results of research on the effect of an external DC electric field on the coefficient of friction of silicone rubber (elastomer) during its rubbing against a steel surface in the „pin–on–disc" experimental set-up. In the tests there were used silicone rubber samples, the pure PAG and PAO synthetic base oils and their blends with an antiwear (ZDDP) additive. The coefficient of friction μ was determined under conditions with and without an external DC electric field. A DC electric field was generated between a silicone rubber sample and a rotating steel disc (a friction pair). A sample holder was electrically isolated from other metal parts of a tribometer and was connected to one of the poles of a DC power supply, while the other pole was connected by means of the carbon brushes to a rotating steel disc. The experimental results show that the external DC electric field established between the rotating steel disc and a silicone rubber sample causes the coefficient of friction to decrease. It was also found that the coefficient of friction μ depends on the steel disc's angular velocity n, the contact pressure p, and the type of base oil and its blends with the additive used.

1. Information

Friction that occurs in the interfacial system: elastomer–oil–steel counter-element (disc) or the so called "pin-on-disc" system causes material wear and energy losses. At the same time friction is reduced with a decrease in the oil viscosity which in turn is significantly related to the oil's temperature increase. These above relationships between different quantities show that the oil's temperature plays an important role in the changes of friction forces.

In order to reduce friction and its consequences one uses different additives and friction modifiers which are added to base oils and are blended to produce formulated lubricants. These lubricants are used to improve the engine oils' exploitation properties including the reduction of friction and materials' wear. All these additives are used to perform crucial and important roles and they are as follows: antiwear, antioxidant, and detergent additives, viscosity improvers, corrosion inhibitors and many others. Some of them exert influence on the physical characteristics of base oils while the other produce a chemical outcome. Often they can produce synergy, but can also cause antagonistic effects [1,2]. These chemical compounds form complex structures and layers on metal surfaces.

Under normal dynamic working conditions the strong deformations of silicone rubber occur that bring about local changes in solid material density and its electrostatic charging. In addition the inhomogeneity of a material's chemical structure on the friction surface can result in some electrochemical phenomena. Therefore micro- and multielectrode electrochemical systems come along which are internal energy sources that are closely related with the electrons' transport (relocation) at the phase boundary. Hence the tribocharging occurs in the friction process and an electric field is generated in a natural way [3].

An external DC electric field exerts a certain effect on a tribological system. The charge transport can change an energy state of the whole interfacial system including the phase boundary.

In the case of the DC electric field the electric energy can play a significant role in the boundary layer formation on the material surface. The external and internal electric fields also arrange and affect the structure of electrical double layers in the case of both solutions and colloidal solutions. On the phase boundaries the electric potential difference always occurs. Under static conditions the potential difference represents an electrical double layer.

* Corresponding author.
E-mail address: juliusz.b.gajewski@pwr.edu.pl (J.B. Gajewski).

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During the relative movement and friction that occur in the friction junction the double layer is disturbed and the local charge density can be different than in other locations and can affect the surface layer structure. These suppositions are based on the authors' former research.

In order to protect the lubricated metal parts of machines (e.g. automotive engines) against wear the antiwear additives (AW), e.g. zinc dialkyldithiophosphate (ZDDP), are used in fully formulated engine oils. ZDDP is also an antioxidant and a corrosion inhibitor. On metal surfaces ZDDP forms a monomolecular layer which protects the surfaces only when the chemical adsorption starts to occur between ZDDP and a metal surface at an elevated temperature that is above 100 °C [4]. The composition and depth of the layer depend on temperature and intensity of friction [1,5].

The nature of ZDDP and the polarity of base oils have an effect on the distribution and durability of the ZDDP layers formed on the metal (here steel) surface and on their tribological behaviour. It was found that any addition of the polar ZDDP molecules to some mineral, non-polar base oils caused a tribolayer to be formed faster and it was thicker than for the blends of ZDDP and synthetic polar oils [6]. The polar ZDDP characteristic (nature) increases the probability that in the case of non-polar base oils more ZDDP molecules could cover the steel surface; it is so because "polarity gives certain molecules a strong affinity for solid surfaces" [7]. Such behaviour of the blends of ZDDP and base oils can make it easier to explain their definite behaviour under dynamic conditions.

The base oils belonging to the same group, e.g., of polar and non-polar synthetic ones differ between each other in their chemical composition that depends on their manufacturer. This results in a difficulty in analysing and explaining the different phenomena that occur, e.g., in the electrical double layers (EDL) on metal surfaces for each of the possible ZDDP–base oil blends. That is why there is a lack of a general, coherent theory about the phenomena and their mechanisms, interactions, static electricity, electro- and tribochemistry that exist in interfacial systems similar to that one being a subject of research and tests presented here.

So far an analysis of the literature of the subject and discussions held during scientific conferences concerning the subject of the research considered do not give any unequivocal answers to questions about the real trend in some processes and phenomena, and the mechanisms that govern them, especially under dynamic conditions. The authors' research on the tribolayers' formation on the surfaces of elastomers and metals in the friction junction in which different commercial base oils with and without additives are used do not indicate their correct interpretation. The elastomer used by the authors in their experiments was silicone rubber. The research results obtained do not allow for any possibility of drawing conclusions from phenomena occurring in the subject friction junction or interfacial system: silicone rubber–oil–steel disc.

2. Experimental materials and measurement

2.1. Materials tested

In the experiments the following base oils were used: PAG ROKOLUB 68 [8] and PAO 6 [9]. The PAG's kinematic viscosities were 66.5 and 10.5 $mm^2\ s^{-1}$ at 40 and 100 °C, respectively and its viscosity index was 146. The PAO's kinematic viscosities were 30.2 and 5.8 $mm^2\ s^{-1}$ at 40 and 100 °C, respectively while its viscosity index was 138. The AW agent was ZDDP 1395 (ZDDP is an antiwear agent) produced by Ref. [10].

The tests on the friction coefficient were carried out for the elastomer made of rubber based on methyl-vinyl-silicone (MVQ) and marked as 70SI by its manufacturer [11].

2.2. Measurements

The tests on the friction coefficient were carried out with and without an external DC electric field generated in a system "pin-on-disc", whose photo as a part of the whole test stand for tribological tests and its schematic diagram are shown in Figs. 1 and 2, respectively.

The silicone rubber sample (1) was placed in a sample holder (2) to which a positive pole of a HV power supply (3) was connected. A negative pole was connected through a carbon brush (4) to a rotating steel disc (5) fixed to a spindle (6). The disc was driven by an electric motor (7) and its angular velocity was regulated by means of a variable-frequency drive iG5A. The measurement of the friction force was performed with the use of a recorder MG-TAE1 (8) accompanied by a load cell NA1 (9). The contact pressure was changed by means of the weights (10).

The sample tested was in the shape of a bolt of 10 mm in diameter and was placed in a metal tool holder. During the tests the sample was pressed against and slid along a disc made of C45 steel of the HRC 58 hardness and of roughness of $R_a = 0.3$ μm. Before the measurements the sample tested was run in using a tribometer along a distance of 20 km with the maximum contact pressure that was used during the laboratory tests. The friction junction was lubricated by means of oil that was on the disc's surface. All the experiments were carried out in the laboratory in which the air temperature and humidity were 21 ± 2 °C and 30 ± 5%, respectively.

In order to perform the tests in which between the elastomer sample and disc the DC electric field was generated, the sample's metal holder was separated galvanically from other metal parts of a tribometer. A positive pole of a DC HV power supply was applied to the holder while its negative pole was connected to a rotating disc with a carbon brush. A DC voltage U_{DC} of 5000 V was applied to the system. During all the experiments carried out the contact pressures p were 0.13, 0.26 and 0.39 MPa and the velocities v of the sample movement relative to the disc were 0.2 and 0.4 m/s. Depending on the different contact pressures and sample velocities the oil's temperature in the friction junction between silicone rubber and a steel disc, as supposed, was different. Therefore the results obtained for the system's different configurations were not compared but the authors paid their attention to the effect of a DC electric field on the friction coefficient at the different system configurations and analysed it carefully.

3. Experimental results and discussion

In Figs. 3–5 there are presented the dependences of the relative friction coefficient μ of the elastomer tested on the „natural" electric field and the external "imposed" electric field for the silicone rubber tested when base oils were used both with and without any additive in the tribological system examined.

The most beneficial effect of the DC electric field on a decrease of the friction coefficient was observed for the PAG base oil with and without the ZDDP antiwear (AW) additive. On average, in most of the cases the friction coefficient decreased by 30%.

In the case of PAO oil with and without AW the slighter reduction in the friction coefficient compared to PAG oil was observed. The addition of ZDDP to the oil caused the greater reduction in the friction coefficient than such an addition of ZDDP to the PAO base oil. Such a change in the friction coefficient resulted from the fact that the PAO oils were nonpolar ones and the use of the AW additive, which is a strongly polar one, caused the increase in the number of particles to occur in the volume of such a blend and which in turn caused the particles to move about in the electric field quite easily. The addition of the ZDDP additive to the strongly polar PAG base oil in turn had no significant effect on the reduction