Laboratory stand for studying the interaction of rubbing bodies in a magnetic field

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Abstract. The paper presents the basic principles for the implementation of experimental studies of the tribological characteristics of friction pairs, taking into account the effect of a magnetic field on them. It has been established that modern experimental studies are carried out on laboratory units using powerful tools to analyze the data obtained, which makes it possible to study the structures of systems by changing the properties of materials under the influence of external factors and wear processes. Taking into account the influence and further research in tribo-conjugated metal bodies (for example, a wheel-rail) of such factors as magnetostriction, external magnetic field (constant, alternating, pulsed), current (direct, alternating, pulsed) passing through the contact, acting both separately, and in various combinations, the design of an experimental laboratory installation was proposed and implemented. The installation allows testing with two types of friction: sliding and rolling with sliding. To measure the friction force (friction coefficient), a 6-wire bridge circuit is used, which is described in the article. The paper shows a diagram of a noise-immune strain-gauge circuit of the installation, which allows a significant level of interference during research. Due to the fact that the friction coefficient with a change in temperature can vary over a wide range, the proposed installation implements a method for automatic temperature compensation in the contact zone of tribological samples. The use of thermocouples is proposed as temperature sensors. The signals from the thermocouples of the installation are transmitted to a measuring device consisting of an analog-to-digital converter and a personal computer. The proposed laboratory setup allows for a wide range of tribological testing studies and monitoring of processes in the friction zone exposed to the magnetic field.

1. Introduction
Experimental studies of the processes occurring in the contact of a wheel with a rail are carried out on roller rigs, in real operating conditions and in laboratory facilities. When using laboratory research, it is easier to follow the principle formulated by V.D. Kuznetsov [1]: "The task of scientific research is to investigate the phenomenon not in all its complexity, but in a simplified form, when of all the factors influencing this phenomenon, only one changes, and the rest remain unchanged."

In [2] it is indicated that about 50% of the tests described in the international journal "Wear", carried out over 13 years, were carried out on laboratory facilities and only 17% - on real machine parts. This confirms the importance of laboratory research, especially since at present powerful tools for analyzing friction surfaces have been developed, which makes it possible to study the structures of systems by changing the properties of materials under the influence of external factors and wear processes. In general, the tribosystem model is shown in Fig. 1.
The allocation of a system allows, firstly, to find its place in the system hierarchy as a subsystem and, secondly, to reduce the number of elements and, accordingly, factors that affect the tribosystem behavior, considering those factors that have a minor effect on the functioning and interconnections of the system's elements.

Back in 1845, Faraday studied the influence of a magnetic field on a number of substances, and after many experiments he wrote: “Now we can assume that all substances are subject to the action of magnetic forces in the same way as the action of gravity, electrical forces and cohesion forces. However, all bodies do not exhibit such magnetism, which is characteristic of iron” [3]. In 1926 E. Herbert described the effect of changing the properties of ferromagnetic materials and their subcultures when exposed to an external magnetic field [4]. The physical nature of the magnetic field effect in the contact area of metal bodies currently has no general explanation. Thus, a number of authors consider the effect of a magnetic field on the martensitic transformation in steel from the point of view of thermodynamic calculation [5].

The authors of [6, 7] explain the increase in the service life of the cutting tool as a result of magnetostrictional and magnetodispersive hardening of steel.

Some hypotheses are based on the presence of a magnetic field in the friction zone. The authors of [6] assume that electromagnetic induction processes can cause changes in the properties of a magnetized instrument. In [8], it is assumed that the increase in the durability of magnetized parts is due to the interaction of excited hydrogen molecules appearing in the contact zone of rubbing surfaces with a magnetic field, which allows for the rapid removal of molecules and atomic hydrogen from the contact zone [9, 10].

In [9, 10], it is indicated that, when exposed to a magnetic field, the location of point defects changes, leading to the appearance of dipoles. The interaction of a magnetic field with dipoles leads to the decomposition of defect complexes.

In [11, 12], it was suggested that during friction of magnetized parts under conditions of boundary lubrication, a decrease in the wear rate may be associated with an improvement in the properties of lubricants under the influence of a magnetic field.
Japanese researchers Hayashi S., Takahashi S., Yamamoto M. [13] noted that an alternating magnetic field facilitates plastic deformation and associated this effect with the characteristics of ferromagnetic materials.

The article [14] considered the effect of an alternating magnetic field on the friction and wear of the XC48 ferromagnetic steel. The magnetic field was created by an alternating current with a frequency of 50 Hz. The experiments were carried out for sliding steel-on-steel contact. When the magnetic field strength changed from 0 to 8 kA/m, the friction coefficient increased from 0.16 to 0.23. In addition, it is noted that there is a decrease in wear, an increase in microhardness, and an increase in tribooxidation of friction surfaces under the action of an external magnetic field.

The introduction of a magnetic field into the contact zone, according to the authors of [15], made it possible to slightly (up to 22%) increase the adhesion coefficient of the wheel to the rail. The authors associate this increase with the increase in the pressure of the wheel on the rail, as well as with physical phenomena occurring on the friction surface. At the same time, it is not specified exactly what phenomena occur in the contact zone. The authors believe that the cost of copper necessary to create a magnetic field will not pay off such a slight increase in the adhesion coefficient.

Nevertheless, the study of the magnetic field influence on the friction surface is of interest in the theoretical aspect and in the field of application to engineering problems. Magnetoplastic effect [16], the essence of which is to weaken the interaction of dislocations with obstacles is known. This effect is manifested in the change: the speed of the macroscopic flow in the surface layer; creep; yield point; internal friction. However, to date, there is no comprehensive explanation of this effect.

In [17] the results of a study to determine the tribological characteristics of a wheel-rail friction pair when exposed to an external constant magnetic field are presented. It is noted that the coefficient of friction increases with increasing magnetic field strength. There is some improvement in the contact surface, in particular a decrease in roughness. It is established that the effect of an electromagnetic field, depending on the level of tension and the state of the intermediate medium, can be both the strengthening of the frictional bonds and their softening.

The work [18, 19] analyzes the points of view of a number of authors on the influence of various factors on the process of adhesion of wheels to rails. The considered factors were divided according to their importance into three groups: main, significant, insignificant. It is indicated that the performed ranking of factors is rather arbitrary. One of the reasons is the presence of incompletely studied factors that do not attract the attention of researchers at the moment due to the difficulties of their theoretical and experimental analysis. So among the insignificant factors is the electric current flowing through the contact. However, in [20], the results of tests of electric locomotives VL22M and VL23 are given, which show that when motors are operating with a current of 250A, the adhesion coefficient is 0.25, and with a current of 500A - 0.49. The influence of an external magnetic field on the processes occurring in the contact zone of metal bodies is not mentioned at all.

In [21, 22], it is noted that the capabilities of the magnetic-pulse processing technology consist in the fact that during the strengthening of parts, one can vary not only the field strength, but also the polarity, duration and amplitude of pulses, as well as the holding time after processing, which is emphasized in some cases after magnetic processing and holding, demagnetization is necessary, which, as a rule, does not reduce the effect of magnetic hardening.

2. Results
Investigation and evaluation of the phenomena occurring in tribo-conjugated metal bodies (for example, a wheel-rail) exposed to such factors as magnetostriction, external magnetic field (constant, alternating, pulsed), current (direct, alternating, pulsed) passing through the contact, acting separately, and in different combinations, demanded to develop an experimental installation, the general view of which is shown in Fig. 2.
**Figure 2.** Installation for studying the tribological characteristics of a friction pair when exposed to a magnetic field: a) in the form of friction - rolling, b) in the form of friction - sliding

The installation is assembled on the basis of a drilling machine. On the shaft 15, containing two bearing assemblies 1, a support disk 4 is installed, on which the coils 5 are located. Coils 5 are located on the casings of 14 of samples 13. Above the cylindrical samples 13, a lower disk sample 6 is installed, on which an indenter 11 consisting of ball bearings, evenly spaced around the circumference of the separator is located. In the center of the separator there is a hole through which it is put on the shaft 15. An insulating sleeve is installed between the shaft 15 and the separator. A textolite mandrel with a holder 8 and a replaceable test disk 7 is inserted into the chuck of the drilling machine 10. The vertical load is set by the device 9. The machine's electric motor is powered by a static frequency converter, which allows smoothly changing the peripheral speed of the holder 8 over a wide range.

To measure the friction force (friction coefficient) a strain gauge 2 with a strain gauge 3 is attached to the shaft 15 through an insulating gasket. To determine the temperature in the contact zone of the rubbing surfaces in samples 13 and disc 6, thermocouples are installed. Samples are made of grade 60 tire steel.

The installation allows testing with two types of friction: sliding and rolling with sliding. In the first case, a disk sample 6 and an indenter 11 are removed from the shaft 15 (Fig. 2 (b)). In the second case, instead of the clips 14 with samples 13, holders are installed. Between the upper ends of holders and the lower end of the disc 6, a slight air gap is created. Electromagnetic coils 5 are attached to the holders.

When studying the effect of magnetostrictive processes on the characteristics of friction pairs, samples 13 were preliminarily magnetized in the magnetic field of a solenoid. The magnetic field strength during pole magnetization was determined by the expression [23]:

\[
H = \frac{1.256nI}{\sqrt{l^2 + D^2}},
\]

where \(I\) – amperage, A; \(n\) – number of solenoid turns, pcs; \(l\) – solenoid length, cm; \(D\) – average diameter of the solenoid turns, cm.

The magnetization of samples 13 made of tire steel occurred in the range of saturation magnetic induction \(B_e \in [1.42 ... 1.50]\) at a strength \(H_e \in [12 \cdot 10^3 ... 15 \cdot 10^3]\).

When investigating the effect of an external magnetic field on the tribological characteristics of a friction pair, electromagnetic coils 15 were used. A storage battery was used to create a constant

magnetic field; for alternating field of different frequency - static converter; for pulsed magnetic field - a capacitor of 600-800 μF.

The transmission of magnetic lines of force through the contact zone in the rolling friction mode is carried out as follows: the magnetic field passes through the first coil holder 5, the air gap, the lower disc 6, the balls of the indenter 11, the upper disc 7, the balls of the indenter, the lower disc 6, the air gap, the second coil holder 5, support disk 4 (Fig. 2, a).

In the sliding friction mode, the magnetic lines of force pass through the first holder 14 with the sample 13, the upper disk 7, the second holder with the sample 13 and the supporting disk 4.

To measure the friction force (friction coefficient), a 6-wire bridge circuit is used, shown in Fig. 3.

![Figure 3. Connection diagram for strain gauges.](image)

To implement this connection diagram, two input channels of an analog-to-digital converter (ADC) are required. The first channel in (Fig. 3) designated as "ADC Input 1" is used to measure the excitation voltage $U_{exc} = U_{gen} + U_{int}$, where $U_{gen}$ – generator voltage, at DC or generator operating voltage at alternating current; $U_{int}$ – voltage of the interferences induced by the electric motor or electromagnetic coils. It should be noted that $U_{exc}$ should be measured directly on the connection diagram, which is especially important when using long wires, since in this case, when the measuring point is removed, the induced interference voltage drops. This fact should be taken into account when using connectors that allow $U_{exc}$ measurement directly on the connector, in this case $U_{exc} = U_{gen}$. In this case, the interference immunity of the circuit will be minimal.

The second ADC channel in (Fig. 3) designated as "Input 2 ADC" is used to measure the total voltage $U_{sum}$ directly on the measuring part of the bridge, while $U_{sum} = U_{gen} + U_{int} + U_{meas}$. After the data on both channels are taken, the difference between the voltage values $U_{sum}$ and $U_{exc}$ is calculated and the measurement signal $U_{meas} = U_{sum} - U_{exc}$ is extracted.

An important role in reducing the influence of interference in the measuring circuit is played by the measuring circuit in Fig. 4. To create a antinterference strain gauge circuit, it is necessary to conditionally divide the sensor leads into the right - "P" (+) and left - "L" (-) (Fig. 4, a), and then, when they are connected to the bridge circuit (Fig. 4, b), it is necessary to connect the left lead of one sensor to the left lead of the other, and the right lead to the right. Thus, a contour is formed in which the EMF induced in different parts of the contour will have opposite directions and the same values, and, accordingly, exclude each other. The signals from the strain gauges are fed directly to the LA-2 USB data acquisition device connected to a computer, manufactured by “Rudnev-Shilyaev” CJSC.
It is known that the coefficient of friction with a change in temperature can drop, increase, and even pass through one or two minima. Temperature measurement at the points of contact of the samples is carried out using thermocouples located in the immediate area of the contacting bodies. In this case, it is important to keep the temperature of the exposed ends constant, as changing it leads to errors. Of all the known methods (baths with melting ice, thermostats, etc.), the most convenient method is to automatically compensate for temperature changes in the free ends. Fig. 5 shows a diagram illustrating a method for automatically compensating the temperature of the exposed ends.

Bridge R is connected in series with the thermocouple TC, in one of the arms of which there is a thermistor $R_0$. The bridge output voltage is proportional to the temperature of the exposed ends of the thermocouple, since $R_0$ is located directly at the point where the exposed ends are soldered. This voltage is subtracted from the EMF of the thermocouple, resulting in automatic temperature compensation of the exposed ends.

The exposed ends of the thermocouples were soldered on special pads (SP). Compensating wires of the gearbox are used as supply wires. The signals from the thermocouples go to the meter M, which consists of an ADC and a computer. The circuit is powered from a stabilized source SS.

3. Conclusion
The above analysis of publications shows the contradictions in the explanation of the principles of magnetostriction, external magnetic field on the tribological characteristics of friction pairs, the absence of a unified theory explaining the essence of the phenomena occurring in the friction zone when exposed to a magnetic field. Thus, it is necessary and urgent to develop a laboratory testing...
facility that allows a whole range of tests and monitoring of processes in the friction zone exposed to the magnetic field.

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