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DESIGN AND TESTING OF A MODULAR TRIBOMETER FOR ANTI-FRICTION COATING ANALYSIS IN OCTG APPLICATIONS

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Abstract: *This study presents the development of a versatile tribometer for pin-on-disk and ball-on-disk configuration for tribological testing of functional coatings. The tribometer is equipped with motor-gearbox (120 Nm, 0–120 rpm), lever system for load application, and bearing assembly for precise force control. Its modular design, featuring ball-on-disk platform with stepper motor-driven positioning of the counterbody, enables flexible configurations for diverse studies. The system employs accessible electronics, including 24-bit ADCs for forces measurement, 16-bit ADC for temperature monitoring, and Arduino Mega board, based on ATmega 2560 microcontroller. Custom software developed in Arduino IDE (for microcontroller) and C# (for PC) facilitates real-time data collecting and analysis. The tribometer's cost-effective and adaptable design ensures high sensitivity and versatility, offering a practical alternative to commercial systems. This work demonstrates an affordable, custom-designed solution which can provide reliable data acquisition for tribological research in OSTG and surface engineering applications.*

Keywords: *versatile tribometer, galvanic coatings, pin-on-disk, ball-on-disk, friction coefficient, wear resistance*

1. INTRODUCTION

Tribological analysis is essential for characterizing the wear and frictional properties of functional coatings in industrial systems. Electrodeposited and anti-friction coatings employed in OCTG pipes threaded connections require comprehensive evaluation of their performance under simulated service conditions [1] as highlighted in recent studies on coating durability under cyclic loads [2]. While offering high measurement accuracy, commercial tribometers are often prohibitively expensive and insufficiently adaptable for specialized research needs [3], particularly for custom coating analysis [4]. The development of a cost-optimized universal tribometer addresses these limitations by enabling both budget-efficient testing and equipment customization for specific research requirements [5].

This work presents the development of a versatile tribometer constructed on a steel base. The device is designed for both pin-on-disk and ball-on-disk testing configurations, specifically optimized for evaluating anti-friction coatings. The article provides a detailed examination of the mechanical design, electronic components, control software, and test results that demonstrate the instrument's capabilities in friction and wear assessment.

2. TRIBOMETER DESIGN

2.1. Mechanical Components

Key components of the tribometer include: steel base (1); gearmotor (2), bearing assembly (3), lever loading system (5), rotating specimen platform (4), strain gauge measurement systems (6, 7) (Figure 1).

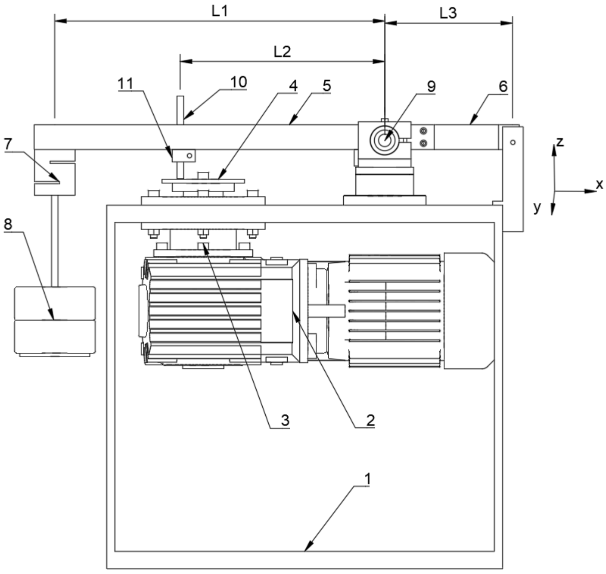

Figure 1. Key components of the tribometer: (1) steel base, (2) gearmotor, (3) bearing assembly, (4) rotating specimen platform, (5) lever loading system, (6) force measurement sensor, (7) weight measurement sensor, (8) load application system, (9) rotating test platform, (10) counterbody, (11) counterbody clamping system.

The gearmotor provides torque output of 120 N·m with a 1:35 reduction ratio, delivering rotational speeds from 0 to 60 rpm (extendable to 120 rpm with enhanced cooling). Speed is precisely controlled through frequency converter. The bearing assembly serves dual functions: it securely mounts the gearmotor while simultaneously providing a stable mounting interface for specimens on the rotating platform.

The lever mechanism (5) simultaneously applies normal load to the counterbody (10) and transmits friction force to the load cell (6). Fabricated as a monolithic component, the lever provides two degrees of freedom (Z- and Y-axis movement).

Load application System (8) is equipped with an additional weight sensor (7) for automatic accounting of the load mass.

For "pin-on-disk" testing the load is created by suspended weights. The force on the pin is calculated as the product of the weight mass and the lever arm ratio (L_1/L_2). The friction force is transmitted to the force measurement sensor through the L_2/L_3 arm.

This design provides high sensitivity and wide load range [6].

A separate platform was developed for testing in the ball-disk system (Figure 2).

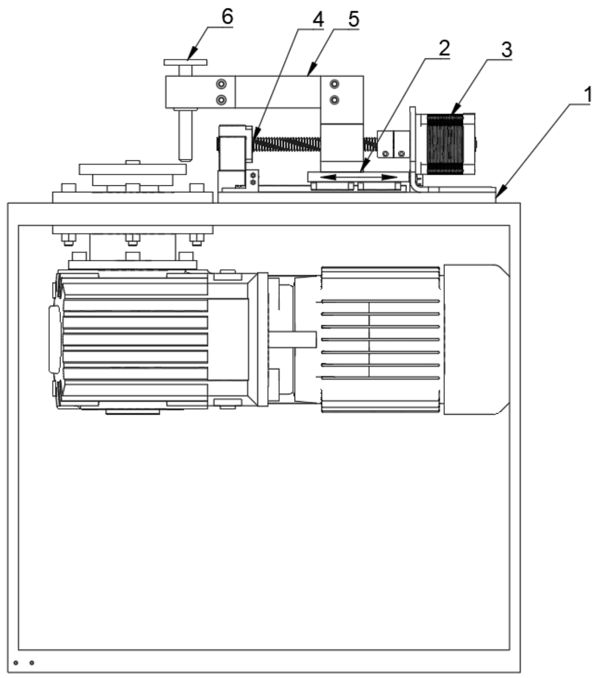

Figure 2. Ball-on-disk platform: (1) base, (2) moving platform, (3) stepper motor, (4) ball screw, (5) force sensor, (6) ball holder.

The platform includes metal base (1) on which a movable plate (2) is fixed, driven by stepper motor (3) using precision ball screw pair (4). The force sensor (5) is cantilevered on the movable plate. The load in the form of weights is applied directly to the ball holder (6), which can move freely along the Z axis in linear bearing.

The platform allows to perform series of experiments on a single sample by precisely adjusting the position of the counterbody relative to the center of the rotating sample.

2.2 Advantages and Limitations

The tribometer design has a number of advantages: simplicity, high sensitivity, wide load range and customization capability. Limitations are related to the labor-intensive calibration process and possible errors due to the pin displacement relative to the tribometer axis. For this purpose, the tribometer design includes adjustment screws to mitigate misalignment issues, a technique validated in similar custom tribometers [7].

3. ELECTRONICS AND SOFTWARE

3.1 Electronic Components

The electronic circuit was developed using Arduino expansion boards. Each module is responsible for specific function in the system.

The friction force and load mass are measured by strain gauges via 24-bit HX711 ADCs.

K-type thermocouples connected to a 16-bit ADS1115 ADC are used to measure temperature. This arrangement provides a resolution of 0.2 °C. A DS18B20 digital sensor is used to compensate for the cold junction temperature of the thermocouples.

An additional ADC is used to continuously measure the electrical resistance between the sample and the counterbody during testing. The frequency converter is controlled by UART-RS485 converter. The rotation speed is continuously monitored by slotted optocoupler. The electronic system is cooled by two fans with PWM control and feedback on the motor temperature level. The emergency stop button increases safety. The operator touch panel serves as an additional interface for interaction with the user.

The modules are assembled on single circuit board, which acts as expansion for the Arduino Mega board (Figure 3).

The equipment also includes additional electronic parts such as power supplies, protection elements, EMI filters.

Figure 3. Main board of the tribometer

The proposed electronic unit circuit is sufficiently reliable and flexible, allowing for repairs and prompt changes to the device's operating logic if necessary.

Figure 4 illustrates the appearance of the tribometer in a fully assembled state.

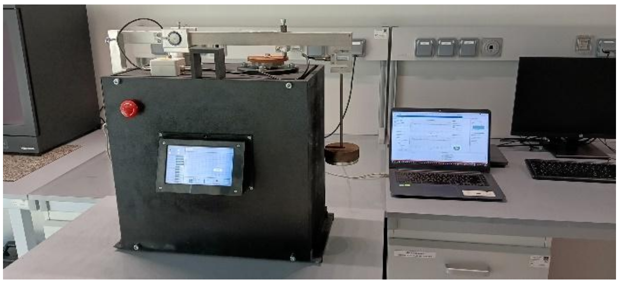

Figure 4. Appearance of the tribometer in a fully assembled state

The tribometer design is optimized for ease of use: the front panel with touch screen and emergency stop button provides intuitive control and increased safety. The ergonomic design minimizes setup time and increases the efficiency of experiments.

3.2 Software

The tribometer system includes three software components: microcontroller firmware, operator panel interface, and PC software. All three programs exchange data with each other and work in tandem. The microcontroller firmware ensures interaction between connected sensors and devices with the PC and operator panel.

The operator touch panel with graphical interface allows to control some parameters and monitor the progress of tests (Figure 5).

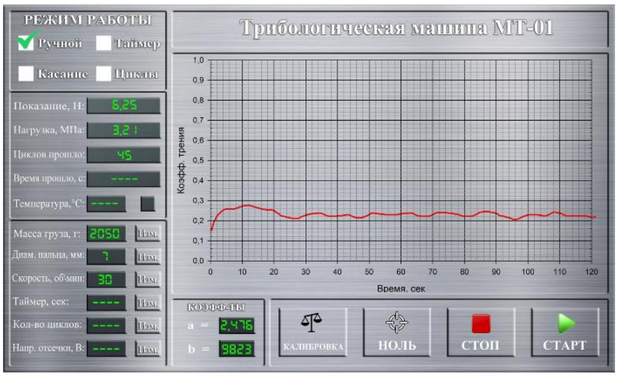

Figure 5. Operator touch panel interface

The PC software TRIBOLOGY-M[1], developed in C#, supports equipment configuration, data exchange, visualization and results export. The main window (Figure 6) includes an area for setting up experimental parameters and an area for plotting graphs.

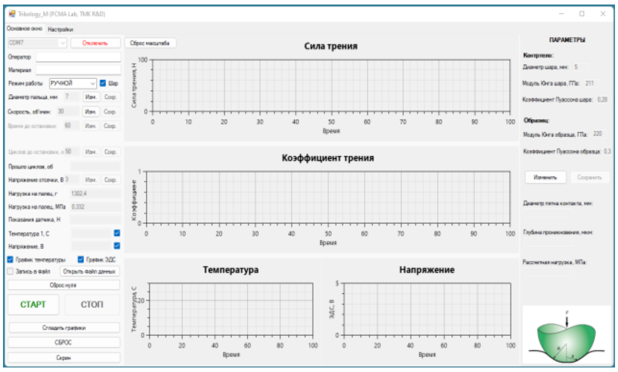

Figure 6. The main window
of the control program TRIBOLOGY-M

The program allows to use six different operating modes: manual, timer, number of cycles, resistance change, static friction determination mode, and the "ball" mode, which is used when using ball-disk attachment. When using this mode, the Hertz theory is used to calculate the contact area, penetration depth, and pressure. Additional software windows are used to configure the device and calibrate strain gauges.

4. PRELIMINARY RESULTS

4.1. Analysis of the coefficient of static friction

Frequency control allows changing the sample rotation speed relative to the counterbody within wide limits – this allows using the equipment for static friction analysis. The method is based on the use of low rotation speeds of the disk relative to the pin. Under load, the pin experiences friction against the disk, and when the critical force is reached, the counterbody is abruptly pulled away. On the graph, this is shown as a smooth increase in friction force followed by a sharp decrease (Figure 7).

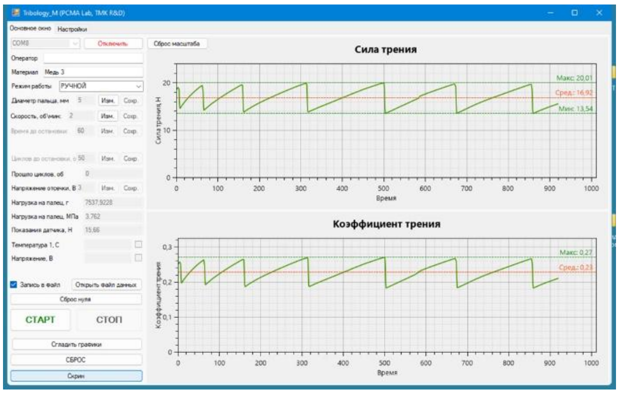

Figure 7. Analysis of the coefficient of static friction

The coefficient of static friction is defined as the average of the maximum values of the friction force.

Figure 7 shows the process of its determination for the friction pair steel pin - steel disk with galvanic copper coating. The value of the static coefficient of friction 0.27 was obtained.

4.2. Dynamic Friction Coefficient Analysis

To analyze the coefficient of friction using consistent lubrication, steel disks (40X steel) with the following coatings were prepared: galvanic copper, TDC and brass (Cold Spray method), used for OCTG threaded connections. 5 mm diameter steel pin was used as counterbody. The coefficient of friction was

[1] The program for controlling the tribological installation, data collection and analysis «TRIBOLOGY-M» is registered under the state registration certificate for computer programs No. 2024684363 dated October 16, 2024.

measured at a pin load of 4 MPa and rotation speed of 30 rpm.

The graphs (Figure 8) show the dependence of the coefficient of friction on time for four types of coatings.

All coatings demonstrate stable behavior after short running-in period. The average values of the coefficient of friction are: 0.13 for the copper coating, 0.15 for brass, 0.12 for TDC and zinc phosphate. The lowest values of the coefficient of friction and the greatest stability were shown by the TDC and zinc phosphate coatings, which indicates their good tribological properties. The brass coating, on the other hand, shows gradual increase in the coefficient of friction, which may indicate slight change in its properties under abrasion or less effective lubrication.

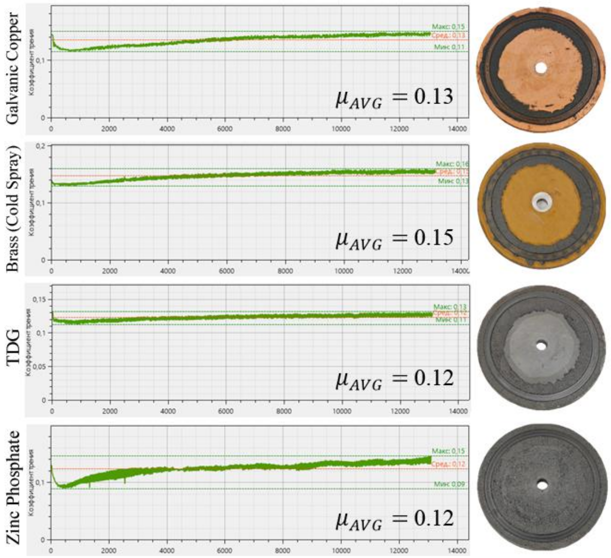

Figure 8. Results of tribological tests

4.2. Wear analysis

The wear resistance of the coatings was assessed until the moment of complete abrasion, which is visually determined by sharp increase in the amplitude of the friction coefficient fluctuations on the graphs. Such drops indicate the emergence of the substrate on the surface and the end of the protective function of the coating. According to the obtained data, the highest wear resistance was demonstrated by the brass coating applied by cold gas-dynamic spraying (Cold Spray), since no pronounced signs of layer destruction were observed throughout the test (Figure 9). This indicates the high strength and resistance of this type of coating to long-term friction loads.

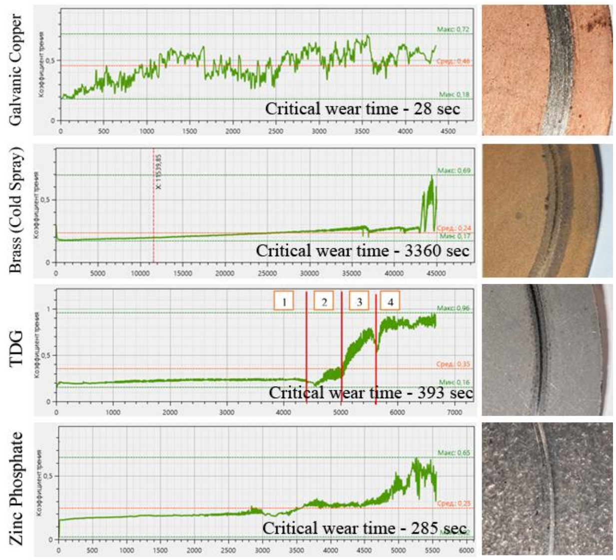

Figure 9. Results of wear tests

The graph for TDG coating (Figure 9) clearly identifies characteristic zones (areas 1, 2, 3, 4) in which a sudden change in the friction coefficient is observed. This phenomenon may be due to the successive wear of the coating layers formed by intermetallic phases of the Fe-Zn system with different chemical compositions and tribomechanical properties [8].

Summing up the results of testing several methods of operation of the tribometer, it can be noted that the system and software are functioning properly, as well as the significance of the results obtained for their further use in scientific activities.

5. CONCLUSION

In response to the growing demand for research into the tribological characteristics of functional coatings, a universal tribometer has been developed and tested. The project development included the manufacture of mechanical, electrical, software and methodological components.

The developed tribometer is economical and universal solution for tribological testing. Its modular design, combining mechanical components with modern electronics and software, ensures high sensitivity and flexibility for specific tasks [3].

A special feature of the equipment is a wide range of capabilities for tribological research. Preliminary tests of threaded coatings confirm the effectiveness of the system in assessing friction and wear parameters.

Prospective areas of development include:
- manufacturing equipment for testing liquid lubricants;
- development of a system for heating samples to temperatures of at least 400°C;
- replacement of the loading system with pneumatic one to implement tests with constantly changing load.

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