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RESEARCH

Development and Experimental Validation of a Pin-on-Disc Tribometer for Friction Testing of Different Metal Materials

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A B S T R A C T

The importance of tribology lies in understanding material characteristics that directly affect the reliability and service life of machine elements. In addition to determining tribological properties, it is necessary to provide experimental conditions that correspond to real operating conditions in order to obtain relevant data on the behavior of two materials in contact. This paper presents the development, construction, and experimental testing of a device for measuring friction force in the contact between two materials. The tribometer described in this study belongs to the Pin-on-Disc type. The normal load is applied by a mechanical system based on weights and a lever mechanism. The variation of friction force is monitored in real time using a load cell and a data acquisition system. Within the experimental study, six test series were conducted. The coefficient of friction was analyzed for the contact between a steel disc and pins made of different materials (steel, brass, and aluminum). After several experimental test series, the obtained results were analyzed. The results of the experimental testing confirm the reliability of the developed tribometer.

1. INTRODUCTION

Product development in mechanical engineering is conditioned by a detailed understanding of material characteristics. One of the key material characteristics are tribological properties. The determination of tribological properties, such as the coefficient of friction, friction force, and wear, represents an important step in predicting material behavior under real operating conditions.

Experimental testing enables the collection of data related to material behavior under various operating conditions [1–3]. Data obtained through experimental investigations can be used for product design optimization and represent an important basis for improving structural design and predicting the service life of machine components [4]. In this study, the process of designing and manufacturing a tribometer is described in detail. The friction force testing device, i.e., the tribometer, was designed, manufactured, and tested at the Faculty of Engineering, University of Kragujevac. After the design and fabrication stages, preliminary experimental testing was conducted and analyzed.

Previous studies on friction and wear have demonstrated that tribological material characteristics have a significant influence on the reliability and efficiency of mechanical components [5]. One of the most frequently investigated tribological parameters is the coefficient of friction. The coefficient of friction depends on the contacting materials, loading conditions, and lubrication regime, and its determination requires both theoretical and experimental investigations [6–8].

Various types of tribometers have been reported in the literature, with the Pin-on-Disc configuration being one of the most commonly used [9–11]. The tribometer described in this paper is based on a mechanical principle of load application and is equipped with its own data acquisition system. Tribometer systems reported in the literature are often structurally complex and significantly more expensive [1,12]. Although such complex tribometer designs provide high measurement accuracy, they are generally less flexible with respect to changes in experimental parameters [13]. The developed tribometer applies the normal load using a system of weights, which is transferred to the pin through a lever mechanism. A lever made of steel components provides a more stable contact between the pin and the disc compared to plastic lever systems reported in the literature [14]. Data acquisition in this type of tribometer is most commonly achieved using electronic components, enabling direct force measurement as well as high accuracy and repeatability of results [15].

Further validation of friction force measurements can include surface topography analysis using profilometry [16]. In addition, optical methods are often employed to determine surface waviness profiles [17]. The effects of friction and wear can also be precisely analyzed using microscopy and spectroscopy techniques [18,19]. An analysis of the available literature indicates a large number of studies focused on the development of laboratory devices for friction and wear testing [20]. As one of such devices, the tribometer represents a reliable system for determining friction force, with the Pin-on-Disc configuration being among the most widely used designs.

The Pin-on-Disc tribometer developed and analyzed in this work provides a stable normal load applied mechanically using weights, which remains constant throughout each test series. The data acquisition system based on a microcontroller and an A/D converter enables reliable and repeatable measurements. The constructed tribometer exhibits the required measurement sensitivity, which is confirmed by clear differences in friction force values resulting from changes in load or material combinations. The obtained coefficient of friction values fall within the range reported in the literature for the same or similar materials. Future research will focus on further improvements of the tribometer, including the integration of a system for automatic determination of the pin track radius on the disc. In addition, further experimental studies are planned for various material combinations under both dry and lubricated conditions.

In this context, the main objective of the present study is to design, construct and experimentally validate a mechanically loaded Pin-on-Disc tribometer with integrated digital data acquisition, and to evaluate its reliability under controlled dry sliding conditions. The specific contribution of this paper lies not in the Pin-on-Disc principle itself, but in the implementation of a mechanically lever-based loading system, the integration of a low-cost high-resolution digital acquisition chain, and the experimental validation through dynamic and statistical analysis of friction behavior. The study also demonstrates that reliable laboratory-scale tribological measurements can be achieved at significantly lower cost compared to commercial systems.

2. PIN-ON-DISC TRIBOMETER

In order to perform the experimental determination of the coefficient of friction in metallic contacts, a Pin-on-Disc tribometer was developed. This section provides a detailed description of the tribometer design process. Basic information on the operating principle is presented, together with a description of the measuring system and the data acquisition procedure used during the experimental investigations.

2.1 Tribometer design

The constructed tribometer belongs to the Pin-on-Disc type. The main characteristic of this type of tribometer is that the contact between two materials is achieved by the rotational motion of the disc, while the pin is fixed in a holder and loaded with a controlled normal load. In addition to functional requirements, economic aspects and ease of use were also considered during the tribometer design process.

Disc rotation is provided by a gear motor with a rated power of 1.5 kW and an output shaft diameter of 25 mm. The tribometer consists of a stationary pin with a diameter of 5 mm and a rotating disc with a diameter of 120 mm and a central bore of 20 mm. The position of the pin is adjustable within a range of 50 to 100 mm from the disc center, which allows multiple tests to be performed on a single disc. The friction force is measured using a load cell with a measuring range of up to 100 N.

The design complies with the requirements of the ASTM G99 standard, including regulation and stability of the rotational speed, as well as a tolerance of the angle between the pin and the disc of ±1° [21].

The tribometer was manufactured using standard steel profiles (50 × 50 × 2.5 mm) and cylindrical elements machined on a lathe and milling machine, while the remaining parts were produced by laser cutting. The structure was designed to allow easy assembly and replacement of components, with all parts connected by welding or bolted joints.

Figure 1 shows the Pin-on-Disc tribometer. The tribometer consists of three subassemblies: the pin holder, the disc holder, and the main structural frame, which also includes the electric motor mount.

Fig. 1. Pin-on-Disc tribometer.

The total cost of manufacturing the tribometer, including components and engineering labor, amounted to approximately €9,650 [22], enabling reliable measurements at a significantly lower cost compared to commercial models. Such a design provides experimental flexibility, precise adjustment of the pin and disc positions, and easy adaptation to different material types and testing conditions.

2.2 Tribometer working principle

The core of the experimental system is a mechanism that ensures stable contact between the pin and the disc. The disc is connected to the electric motor shaft via a coupling and performs controlled rotational motion, while the pin is mounted in a holder equipped with a system for applying the normal load. The normal load is applied using weights, thereby ensuring contact between the tested surfaces. Figure 2 shows the main components of the developed Pin-on-Disc tribometer.

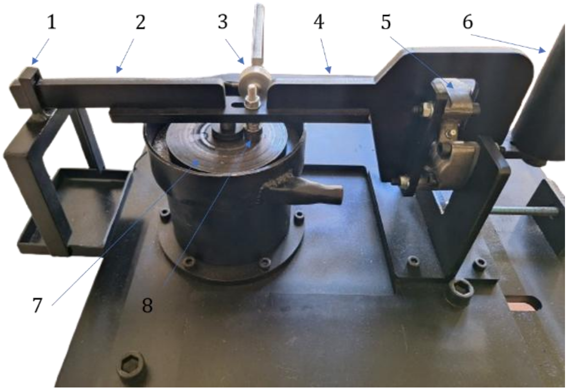


Fig. 2. Tribometer essential parts.

The constructed tribometer consists of the following elements:

1. Weight carrier
2. Connection between the weight carrier and the pin ER11 collet carrier
3. Load cell
4. Cardan joint holder
5. Cardan joint
6. Balancing weight
7. Disc
8. Pin ER11 collet carrier and pin

The application of the normal load disturbs the equilibrium of the system; therefore, an articulated mechanism (Cardan joint) is incorporated into the design to allow adjustment of the pin position. The Cardan joint ensures stable contact and uniform load distribution during the experiments. After force equilibrium is established, contact is achieved between the rotating disc and the stationary pin, with the pin producing a wear track on the disc surface.

The coefficient of friction is determined based on the ratio of the friction force to the normal load [18]:

$$\mu = \frac{F_\mu}{F_n} \qquad (1)$$

The normal load is applied through a lever mechanism with a transmission ratio of 2:1. Therefore, the applied weight produces a doubled normal load at the contact point. Normal load$F_n$seis calculated from weight mass, where lever mechanism is designed to increase contact force as in the equation (2) [22]:

$$F_n = 2 \cdot m \cdot g \qquad (2)$$

where m is the applied mass and g is gravitational acceleration (9.81 m/s^2). The lever-based amplification ensures stable and repeatable load transfer to the contact interface.

The friction force was determined experimentally using a load cell, thereby providing all the parameters required for calculating the coefficient of friction during the tests.

2.3 Data acquisition

For the experimental determination of the friction force using the developed Pin-on-Disc tribometer, the normal load in the contact between the pin and the disc was applied using weights. The normal load remained constant throughout each test series. The friction force generated at the contact between the pin and the disc was measured using a load cell with a nominal capacity of 100 N and manufacturer-declared non-linearity below ±0.03 % of full scale. The sensor was connected to a computer via an Arduino Uno R3 microcontroller and an HX711 A/D converter, which enable the digitization of analog signals from the sensor. Figure 3 illustrates the connection scheme of the Arduino microcontroller and the A/D converter.

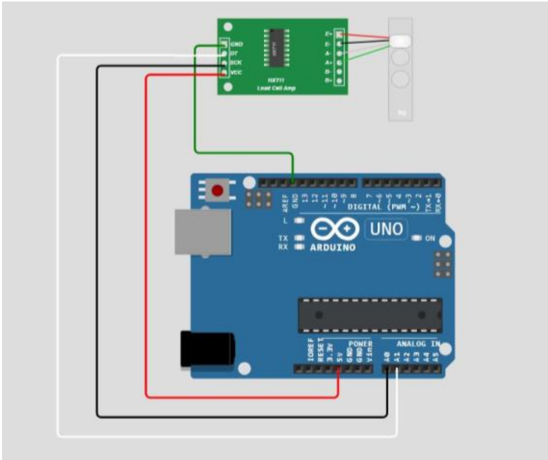


Fig. 3. Schematic of connection between Arduino controller and A/D converter.

Measurements are acquired in real time using Telemetry software, which enables continuous monitoring of the friction force and recording of its variations during the experiment. The system also allows sensor calibration and adjustment of measurement parameters, thereby achieving high accuracy and reproducibility of the acquired data. The Telemetry software enables data digitization and storage in CSV format. This format allows further processing and analysis of experimental data using standard software tools for statistical analysis and signal processing. Before each test, the load cell was calibrated using certified reference weights to ensure measurement accuracy. Zero-offset compensation was performed prior to each measurement to eliminate baseline errors. Sensor drift was continuously monitored to account for any temporal variations. The acquired signal was processed using a digital moving-average filter to reduce noise, ensuring stable and reliable readings. Measurement repeatability was evaluated through three repetitions of each test condition. The uncertainty of the friction coefficient was estimated using error propagation principles, and the statistical analysis was conducted at a 95 % confidence level. Laboratory ambient temperature was maintained at 23 ± 2 °C to minimize thermal effects on sensor performance.

2.4 Testing experiments

Preliminary testing of the coefficient of friction involved investigating the coefficient of friction for different combinations of metallic contacts. The following material combinations were examined:

1. Steel disc (S355) and steel pin (C45)
2. Steel disc (S355) and brass pin
3. Steel disc (S355) and aluminum pin (AlMgSi1 – EN AW-6082)

For each of the above material combinations, two test series were conducted, with variation of the normal load, i.e., the applied weight. In the first test series, a weight of 2 kg was used, while a 4 kg weight was applied in the second test series. During each test, the pin traveled a sliding distance of 500 m. In order to determine the exact time required for the pin to travel a distance of 500 m, the following procedure was applied. The rotational speed of the electric motor was determined using Equation (3) [23]:

$$n_{EM} = \frac{120 \cdot f}{P} \tag{3}$$

where:

f – electric motor frequency and

P – electric motor number of poles.

The motor speed frequency was constant during testing, and it was 50 Hz. Four poles electric motor was used, with factory designation 6T190L4 [22], so number of poles is $P = 4$. With inserting values into the Equation (3) it is obtained that rotations per minute of electric motor was $n_{EM} = 1500\, min^{-1}$. After that, the number of revolutions of the disc driving shaft was easily calculated and is given as follows [23]:

$$n_{Disc} = \frac{n_{EM}}{i} = \frac{1500}{15} = 100\, min^{-1} \tag{4}$$

where i represents the gear ratio of the reducer.

Using the number of revolutions per minute of the disc (n_{Disc}), the angular speed of the disc is calculated [23]:

$$\omega_{Disc} = \frac{\pi \cdot n_{Disc}}{30} = \frac{\pi \cdot 100}{30} = 10.47\, s^{-1} \tag{5}$$

Angular speed was used for determining the linear sliding speed in contact ($\boldsymbol{v}$), where the radius of disc is of crucial influence as well ($\boldsymbol{r}$) [23]:

$$v = r \cdot \omega \tag{6}$$

Size of the radius (r) was varied during the testing in order to get new contact track for each experiment. This is achieved by a simple adjustment of the lever belonging to the pin holder subassembly. Changing the radius allows multiple tests to be performed on a single disc. In addition, variation of the radius along which the pin moves on the disc affects the linear sliding velocity and, consequently, the time required for the pin to travel a distance of s = 500 m. This time is determined using the following equation [23]:

$$t_{(500\,m)} = \frac{s}{v} \tag{7}$$

In Table 1 is given the plan of experiment or tribometer test run.

Table 1. Plan of the experiment for tribometer test run.

No.	Disc Material	Pin Material	*r* (m)	*t* (min)	F_n (N)	*v* (m/s)
1	Steel	Steel	0.051	15.6	39.24	0.534
2	Steel	Steel	0.048	16.58	78.48	0.503
3	Steel	Brass	0.045	17.68	39.24	0.471
4	Steel	Brass	0.04	19.89	78.48	0.419
5	Steel	Aluminum	0.036	22.11	39.24	0.377
6	Steel	Aluminum	0.03	26.53	78.48	0.314

Where F_n represents the normal load, where m denotes the mass of the applied weight. The radius of the circular path traced by the pin during sliding on the disc is denoted by r, while t represents the time required for the pin to travel a distance of 500 m at different disc sliding speeds v. The normal load value of F_n = 39.24 N from Table 1 corresponds to a contact pressure of 2 MPa, where as F_n = 78.48 N corresponds to a contact pressure of 4 MPa. Each test series was conducted under dry (unlubricated) operating conditions.

Figure 4 shows the experimental setup during testing, specifically the third test series. In this experiment, the variation of the friction force over time was recorded for the contact between a steel disc and a brass pin. The normal load was applied using a 2 kg weight and amounted to 39.24 N.

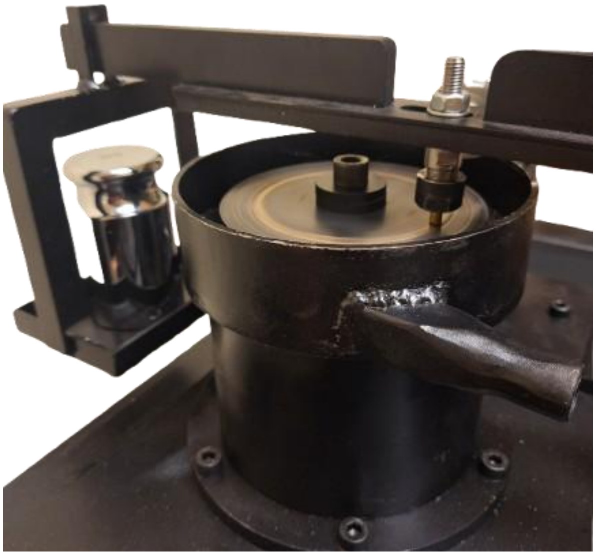


Fig. 4. Experimental determination of the coefficient of friction in the contact between steel and brass.

The hardness values of the pin and disc materials are presented in table 2, along with the surface roughness parameters prior to testing. The average surface roughness parameter Ra was measured for each surface in three repetitions, after which the obtained values were averaged in order to increase the reliability of the measurements.

Table 2. Hardness and surface roughness of materials before testing.

Material		Hardness values, Brinell	Surface roughness, Ra [μm]
Disc	S355JR	165 HB	0.917
Pin	C45	190 HB	0.867
	Brass	100 HB	0.985
	AlMgSi1	65 HB	0.891

The sample preparation included a grinding procedure up to P1200 grit, followed by ultrasonic cleaning in ethanol to remove residual contaminants and ensure reproducible contact conditions. The tests were conducted under dry sliding conditions at a temperature of 23 ± 2 °C, with relative air humidity in the range of 45–55%.

3. RESULTS AND DISCUSSION OF TRIAL TESTS

In this section, the experimental results obtained from the investigation of the coefficient of friction using the developed Pin-on-Disc tribometer are presented and analyzed. The analysis was carried out by monitoring the dynamic behavior of the friction force and the coefficient of friction during sliding, examining the influence of the normal load, and performing statistical data processing in order to evaluate the stability and repeatability of the measurements. The obtained results provide the basis for validating the functionality and reliability of the developed tribometer.

3.1 Dynamic behavior of friction force and friction coefficient

Figures 5 and 7 show the variation of the coefficient of friction as a function of the sliding distance for the contact between a steel disc (S355) and pins made of steel (C45), brass (CuZn37), and aluminum (AlMgSi1).

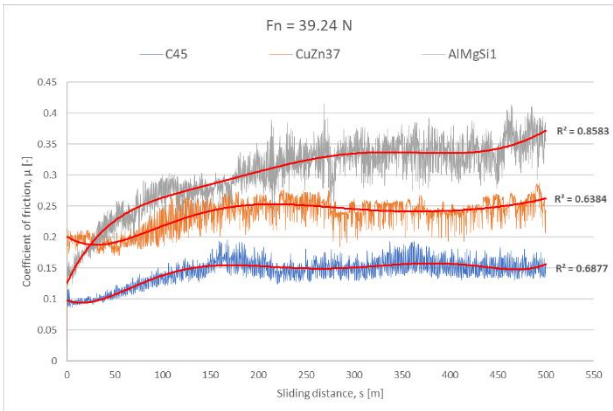


Fig. 5. Dynamic friction coefficient $\mu_{(s)}$ for $F_n = 39.24$ *N.*

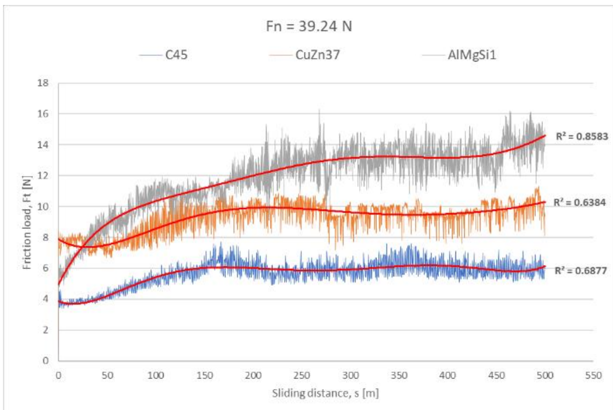


Fig. 6. Dynamic friction $F_{t(s)}$ for $F_n = 39.24$ *N.*

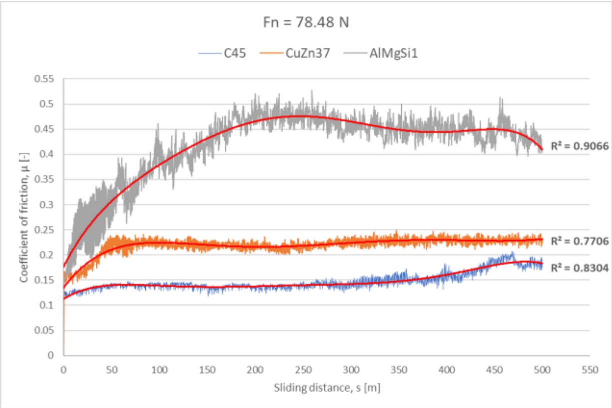


Fig. 7. Dynamic friction coefficient $\mu_{(s)}$ for F_n *=78.48 N.*

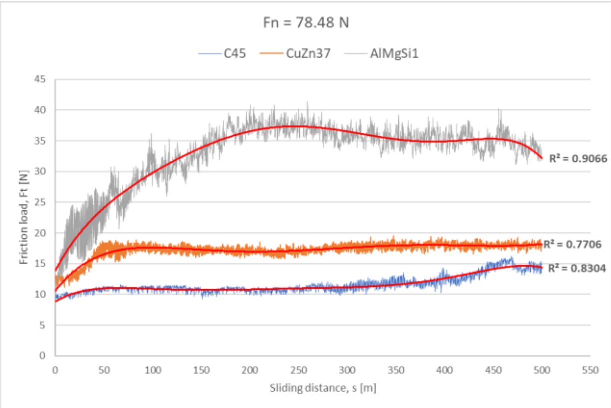


Fig. 8. Dynamic friction $F_{t(s)}$ for F_n *= 78.48 N.*

The diagrams in figure 5 correspond to a normal load of F_n = 39.24 N, while those in figure 7 present the results for a normal load of F_n = 78.48 N. Figures 6 and 8 show the corresponding changes in friction force as a function of sliding distance for the same normal loads.

For all investigated material combinations, and for both normal loads, a characteristic running-in phase is observed at the beginning of the tests, during which a rapid increase in the coefficient of friction occurs. This phase is associated with the adaptation of the contact surfaces, removal of initial surface asperities, and the establishment of stable real contact between the pin and the disc. After completion of the running-in phase, the system enters a quasi-steady friction regime, in which the coefficient of friction stabilizes around a mean value with relatively small fluctuations.

Analysis of the results indicates that the lowest values of the coefficient of friction were recorded for the steel–steel (C45) contact, while higher values were obtained for the steel–brass contact, and the highest values for the steel–aluminum contact. This trend is consistent with the well-known tribological behavior of metallic pairs and can be related to differences in mechanical properties of the materials, primarily hardness, plasticity, and tendency toward adhesion. In the case of aluminum, a more pronounced adhesive component of friction is observed, leading to higher coefficient of friction values and increased fluctuations during the tests.

The variation of the friction force overtime exhibits a trend similar to that of the coefficient of friction, confirming the consistency of the obtained results. Good correlation between the friction force and the coefficient of friction, as well as a stable signal during the quasi-steady regime, indicate reliable operation of the measuring system, appropriate tribometer design, and stable contact conditions throughout the experiments.

3.2 Influence of the normal load on friction coefficient

By comparing the results obtained at normal loads of F_n = 39.24 N and F_n = 78.48 N, an increase in the coefficient of friction with increasing load can be observed, particularly pronounced for the steel–aluminum contact. This behavior can be attributed to more intensive adhesive processes, an increased real contact area, and more pronounced plastic deformation of the softer material at higher normal loads. For the steel–steel and steel–brass contacts, the influence of the normal load is significantly less pronounced, indicating more stable tribological behavior of these material pairs within the investigated load range. These results confirm the capability of the developed tribometer to detect changes in friction resulting from variations in the normal load, which is of particular importance for the experimental analysis of different operating conditions.

3.3 Statistical analysis of friction coefficient

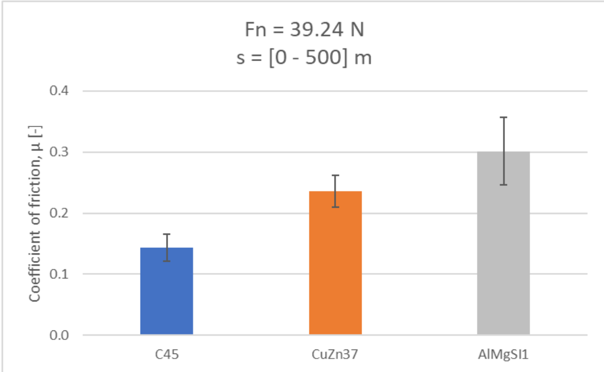
For a quantitative evaluation of friction stability and measurement repeatability, statistical analysis of the experimental data was performed for two sliding intervals: the entire test interval (s = 0-500 m) and the stabilized interval (s = 400-500 m). The mean values of the coefficient of friction, standard deviations, and ±3σ ranges are presented in table 3.

Table 3. Average values of the friction coefficient and standard deviation ±3σ

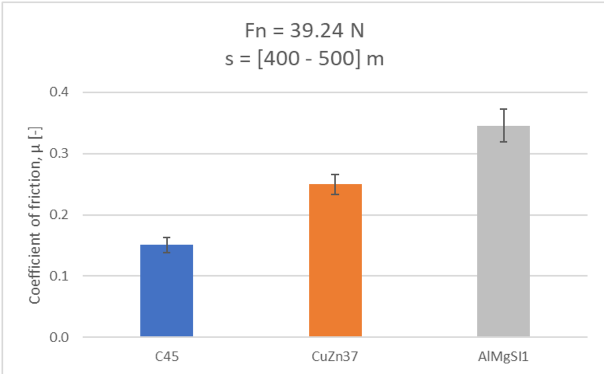
s = [0 – 500] m			
F_n = 39.24 N	μ_{sr}	σ	±3σ
C45	0.144	0.022	0.066
CuZn37	0.236	0.026	0.079
AlMgSI1	0.301	0.055	0.166
s = [400 – 500] m			
F_n = 39.24 N	μ_{sr}	σ	±3σ
C45	0.151	0.012	0.037
CuZn37	0.250	0.016	0.048
AlMgSI1	0.345	0.027	0.081
s = [0 – 500] m			
F_n = 78.48 N	μ_{sr}	σ	±3σ
C45	0.148	0.018	0.055
CuZn37	0.219	0.018	0.053
AlMgSI1	0.418	0.072	0.216
s = [400 – 500] m			
F_n = 78.48 N	μ_{sr}	σ	±3σ
C45	0.177	0.014	0.043
CuZn37	0.229	0.006	0.019
AlMgSI1	0.442	0.019	0.058

The results show a reduction in standard deviation in the stabilized friction regime, indicating contact stabilization and good measurement repeatability. The smallest variations were recorded for the steel–steel contact, while larger fluctuations were observed for the steel–aluminum contact, particularly at higher normal loads, which is consistent with its more pronounced adhesive character.

The bar charts presented in figures 9a–9d show the mean coefficient of friction values for different material pairs under two normal loads and two sliding intervals (0–500 m and 400–500 m). Figures 9e and 9f provide a comparative overview of the influence of normal load for F_n = 39.24 N and F_n = 78.48 N, respectively. The bar charts presented in figure 9 provide a clear visual representation and comparison of the mean coefficient of friction values for different material pairs and loading conditions. The consistent ranking of coefficient of friction values for all analyzed cases further confirms the stability of operation and validity of the developed tribometer, as well as its suitability for experimental tribological investigations.



(a)



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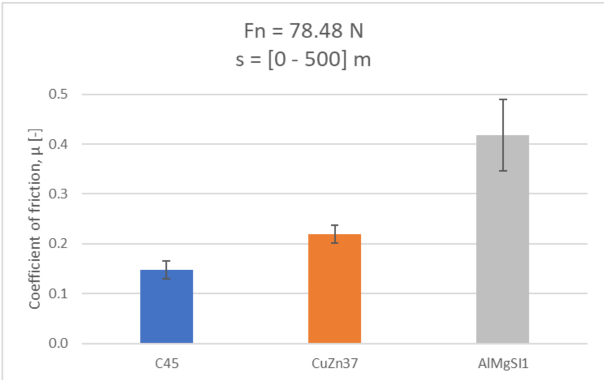
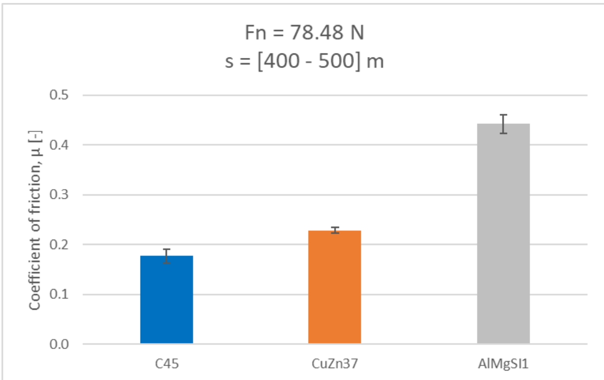
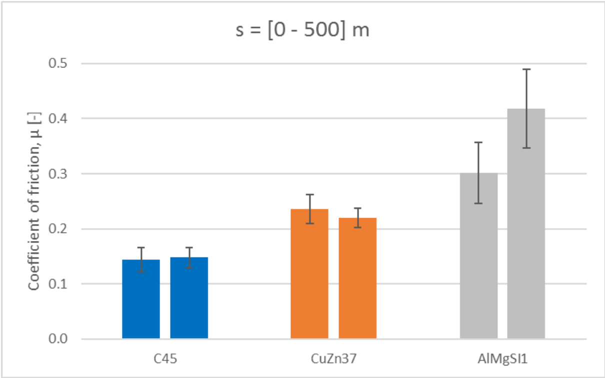


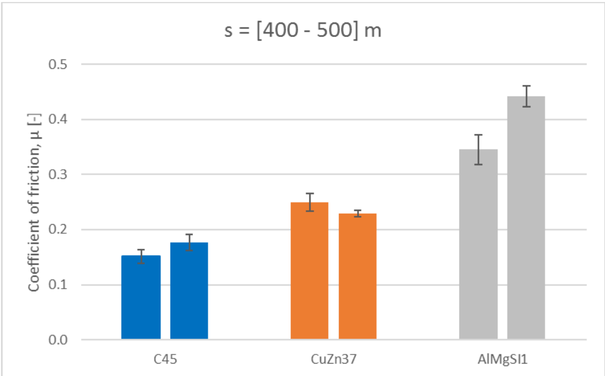
(c)



(d)



(e)



(f)

Fig. 9. Friction coefficients of different Pin-on-Disc pairs: (a) F_n = 39.24 N, sliding interval 0–500 m; (b) F_n = 39.24 N, sliding interval 400–500 m; (c) F_n = 78.48 N, sliding interval 0–500 m; (d) F_n = 78.48 N, sliding interval 400–500 m; (e) comparative diagram of normal load F_n = 39.24 N; (f) comparative diagram of normal load F_n= 78.48 N

The separation of the running-in and quasi-steady friction regimes eliminates the influence of initial instabilities on the evaluation of the coefficient of friction. The reduction in data scatter within the stabilized sliding interval confirms that the developed tribometer provides stable experimental conditions and reliable monitoring of the friction force over time. The obtained results indicate that the observed differences in coefficient of friction values arise from the actual tribological characteristics of the investigated material pairs, rather than from measurement uncertainties or system instabilities. This confirms that the developed Pin-on-Disc tribometer is suitable for experimental tribological investigations and for comparative analysis of different material combinations and loading conditions.

The present study primarily focuses on friction-force measurement and mechanical validation of the developed tribometer. Detailed wear mechanism analysis (e.g., SEM or EDS characterization) was not included in this initial validation phase. However, the system enables wear-track evaluation by mass-loss measurement or profilometric analysis, which will be addressed in future studies.

Several repetitions were performed for each test condition, confirming stable and reproducible tribometer behavior. Future studies will include more detailed statistical analysis to further validate the system and confirm measurement repeatability.

4. CONCLUSION

This paper presents the development, construction, and experimental validation of a Pin-on-Disc tribometer intended for determining friction force and the coefficient of friction in metallic contacts. The developed tribometer enables the application of a stable normal load through a mechanical system based on weights and a lever mechanism, as well as reliable real-time measurement of friction force using a load cell and a data acquisition system.

Experimental investigations conducted on different combinations of metallic materials revealed characteristic dynamic friction behavior, with a clearly pronounced running-in phase followed by a transition to a quasi-steady regime. The observed differences in coefficient of friction values among the investigated material pairs are consistent with the known tribological characteristics of the materials, thereby confirming the correctness and sensitivity of the measuring system. The analysis of the influence of the normal load showed that an increase in load leads to higher values of the coefficient of friction, particularly for the steel–aluminum contact, which can be attributed to more pronounced adhesive processes. Statistical analysis of the results indicated reduced data scatter in the stabilized friction regime, confirming good repeatability and reliability of the measurements.

Based on the obtained experimental results, the coefficient of friction for the tested material pairs ranged from 0.144 to 0.442, with the maximum measured friction force reaching 45.5 N, corresponding to the aluminum-on-steel contact under the higher normal load. Analysis over the entire sliding distance (0–500 m) revealed a characteristic running-in phase with higher standard deviation of coefficient of friction, while in the final segment (400–500 m) a significant reduction in deviation was observed: for C45 from 0.018 to 0.014, for CuZn37 from 0.018 to 0.006, and for AlMgSI1 from 0.072 to 0.019, indicating stabilization of the friction regime. For the AlMgSI1 contact, the coefficient of friction increased from 0.418 to 0.442 in the final segment, corresponding to a percentage rise of approximately 5.7%, while changes for the other materials were less pronounced. These results confirm the sensitivity of the tribological system to normal load and demonstrate the reliability and accuracy of the developed tribometer. Based on the obtained results, it can be concluded that the developed Pin-on-Disc tribometer represents a reliable and flexible experimental system suitable for laboratory and research tribological investigations. The developed device enables comparative analysis of different material pairs and loading conditions at significantly lower cost compared to commercial tribometers, making it suitable for both research and educational purposes.

Future research will focus on further improvements of the developed tribometer, primarily through the expansion of its experimental capabilities and more detailed analysis of wear processes. This includes the application of profilometric and microscopic methods for wear track characterization and correlation of friction mechanisms with surface morphology. In addition, future studies will address the influence of lubrication, different sliding velocities, wider ranges of normal loads, and other material combinations. Such an approach will enable a more comprehensive tribological characterization of materials and further validation of the developed tribometer under various operating conditions. Further investigations will include surface morphology analysis and correlation between friction behavior and wear mechanisms in order to achieve comprehensive tribological characterization of the tested material pairs.

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