

Article

A Two-Stage Self-Aligning, Two-Sided Flat-on-Flat Friction-Measurement Device for Universal Testing Machines Under Elevated Contact Pressures

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Abstract

The precise determination of the coefficient of friction is of fundamental importance in many engineering applications, especially in cases where different material pairs, surface-treated systems, polymers or coated surfaces come into contact with each other. Classical tables of friction data can often only be used as approximate values, since friction behavior is considerably influenced by surface pressure, sliding velocity, contact geometry and the condition of the surfaces. In this article, we present the principle, structural design and application possibilities of a new friction-measuring device that can be adapted to a universal testing machine (UTM). Our device provides a symmetric, two-sided flat-on-flat contact configuration, a closed loading system and a two-stage self-aligning mechanism, with adjustable normal load. The relevant rotational axes are positioned in the contact planes to reduce parasitic moments and the coupling between the tensile measuring force and the applied normal load, thereby reducing a potential source of measurement variability. With the device, both static and dynamic friction coefficients can be determined (and the transition ranges can be explored in detail), at different nominal contact pressures (p , up to 50 MPa) and sliding velocities (v , mm/min). The demonstrative measurement results show that the system is suitable for the separate examination of the characteristic stages of the friction process, such as the initial force build-up, the static friction maximum and the steady-state dynamic range.

Keywords: friction coefficient measurement; flat-on-flat friction; universal testing machine; static and dynamic friction; high contact pressure



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1. Introduction

The concept of the coefficient of friction has long been known in science and engineering. The phenomenon of friction was first studied scientifically by Leonardo Da Vinci, but his notes presenting the theoretical background of bodies moving over each other have not become widely known [1,2]. Knowing the coefficient of friction is also important in many areas of our daily lives, as there is a connection, for example, between road friction and traffic safety [3] and the braking distance of vehicles [4]. The distribution of friction conditions along the road and the change in the friction conditions of the road surface depending on the seasons also greatly affect traffic safety [5]. The occurrence of accidents is also related to the characteristics of the friction conditions between shoe soles and the ground, as well as the dirt on shoe soles and the ground, so shoe manufacturers must take

these factors into account during design [6,7]. Determining the coefficient of friction experimentally is essential for the development of reliable models of rock sliding that can be used for earthquake simulations [8]. In flood protection, the coefficient of friction of open-topped woven polypropylene cellular containers filled with dense granular sand relative to the substrate fundamentally determines the load-bearing capacity of the protection structure, so knowledge of the coefficient of friction is also essential for the design of flood protection systems [9]. In the world of sports, the friction between the finger pad/palm and the sports equipment greatly influences the performance of the athlete; therefore, the tribology of the skin plays a key role in the optimization of sports equipment [10]. In the winter sport of bobsleigh, knowing the friction between the sole of a runner's shoe and the ice surface is essential for understanding the dynamics of the sport [11]. In industrial processes, knowledge of the friction coefficient is also very important; for example, in sheet metal forming [12,13], deep drawing [14], or in the optimization of the ejection system in the injection molding cycle, detailed knowledge of the friction properties of the contacting metal-metal and metal-polymer surfaces is essential [15].

Although, based on the above, knowledge of the coefficient of friction is crucial in many areas and can usually be determined relatively easily experimentally, the fundamental physical background of the phenomenon is far from trivial. The coefficient of friction is a dimensionless quantity defined as the ratio of the friction force (F_f , N), acting parallel to the contact surface and opposing relative motion, to the normal force (F_n , N), acting perpendicular to the contact surface. The definition is valid both at the threshold of the start of movement (static coefficient, μ_0) and during actual sliding (dynamic coefficient, μ_{dyn}). This simple ratio conveniently illustrates how easily a pair of materials slide over each other under given conditions; the static (μ_0) and dynamic (μ_{dyn}) coefficients of friction (Figure 1b) can be given with the following equations:

$$\mu_0 = \frac{F_{friction\ max}}{F_n} \quad (1)$$

where $F_{friction\ max}$ is the maximum of the registered force value (here local displacement speed is close to zero).

$$\mu_{dyn} = \frac{F_{friction}}{F_n} \quad (2)$$

where $F_{friction}$ is the near-steady state of the registered force (gross sliding—see Figure 1b) at a constant sliding velocity.

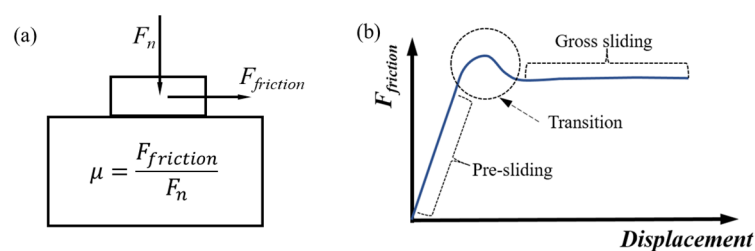


Figure 1. (a) Definition of the coefficient of friction; (b) classical friction coefficient change curve as a function of time or displacement.

Although the measurement of static and dynamic friction coefficients under laboratory conditions seems to be a relatively simple task, it is extremely difficult to accurately determine the time- and condition-dependent (e.g., temperature, humidity, preload conditions, etc.) friction characteristics of clean, lubricated or contaminated surfaces with realistic geometry and also to predict the conditions of friction. The literature usually classifies actual friction occurring in practical applications into one of the four categories in Figure 2.

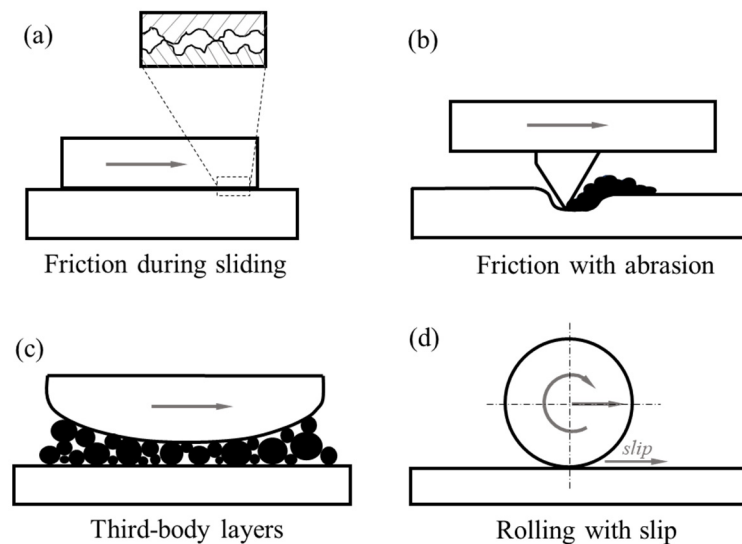


Figure 2. Types of friction. (a) Friction during sliding; (b) Friction with abrasion; (c) Third-body layers; (d) Rolling with slip.

A number of friction-measuring devices have been developed for the investigation of these friction phenomena [16]. Blau [17,18] classifies them into six groups based on their operating principle:

1. Gravitation-based/inclined-plane devices: The principle of measurement is that a body is pulled/slid on an inclined plane or in a simple sled system, where the load (dead-weight) and the geometry (e.g., inclination angle) are known. The coefficient of friction is typically determined from equilibrium conditions (starting angle, steady-state sliding condition). This method is simple, inexpensive, and suitable for educational purposes. The disadvantage is that it has limited accuracy, and speed, pressing force and environmental conditions can only be controlled to a limited extent.
2. Direct linear force-measurement devices: The frictional (tangential) force is measured directly with a load cell, often in addition to measuring/controlling the normal force (F_n). Typical examples include the following: pin-on-disk (when the tangential force is measured with a force arm/cell), reciprocating/ball-on-flat, flat-on-flat, and pull-out/pull-through systems.
3. Torque-measurement devices: These are particularly suitable for friction measurements in rotating motion (e.g., brakes, bearings, seals, clutches). Friction is calculated from the measured torque (M), the load and the geometric parameters (effective radius/lever). The advantage is that it models practical rotating systems well; the disadvantage is that a geometric/contact model is required to calculate μ .
4. Tension-wrap/capstan devices: This method is used for tensioned tapes, wires, ropes or yarns. Friction is determined from the difference between the input and output tension force (and the wrap angle). It has the advantage of specifically describing “wrap” industrial situations but can be sensitive to wrap conditions and surface conditions.
5. Oscillation-decrement/oscillatory dissipation devices: Friction is calculated from the decrease in the amplitude of oscillation or the energy dissipation of the system.
6. Indirect indicators/indirect measurements: Indirect signs of friction are measured, e.g., motor current/power, or temperature change/heat generation. In this case, the coefficient of friction can be estimated indirectly by modeling. The advantage is easy integration (e.g., operational monitoring); the disadvantage is indirectness and the resulting greater uncertainty.

Based on the above, friction-measuring devices have been designed for many industrial applications or material pairs. James and Newell [19] published a study in 1980 describing a friction-measuring device with a vertical plane and rigid design that can be adapted to a tensile machine. It is suitable for measurements that are not sensitive to the stick–slip phenomenon. It takes advantage of the wide speed range and control options of the tensile machine. The case study (polyurethane–metal, rubber–glass) demonstrates that it is not practical to characterize friction with a single μ value, since speed and temperature also affect the coefficient of friction. The authors draw attention to the importance of run-in cycles (50 cycles/sample pair). Benabdallah and Chalifoux [20] further refine the previous approach by describing a computer-controlled, reciprocating plane-to-plane tribometer head that can be attached to a hydraulic testing machine, in which nominal surface pressure can be interpreted well and the static and dynamic friction coefficient can be measured with programmable measurement cycles and high-frequency data acquisition. Oloffson and Holmgren [21] describe a servohydraulic tension–torsion machine that can be used at low sliding velocity (down to 3 nm/s). Dunkin and Kim [22] developed an experimental device for studying friction under similarly low-load conditions, the so-called centrifugal friction apparatus (CFA), which can measure the static coefficient of friction between flat surfaces at very low normal forces. Gasco and Rodriguez [23] describe three types of devices for measuring the friction of polymer films. In each device, a moving element with two identical polymer surfaces slides between two stationary blocks covered with the same polymer. Moro et al. [24] developed a special device for measuring the friction between tendon and bone. The friction force and the static/dynamic friction coefficient are calculated from the difference in tensile force measured at the two ends of the tendon, while the prestressed tendon moves at a speed of 2 mm/s. Bergström et al. [25] developed a small portable friction-measuring device that can be used for measuring the friction of bicycle paths. The device can be used to rate road surface materials under different weather conditions, and the measurement data can provide a basis for the design of bicycle paths and their maintenance schedules. Wang et al. [26] presented a Mesoscale Friction Tester, which can exert forces between 10 nN and 1 mN on a contact radius between 10 nm and 10 μ m. Lahayne et al. [27] in 2009 presented the Linear Friction Tester (LFT) developed at TU Wien, which uses a linear drive to pull a test piece (typically rubber) fixed on a sled over interchangeable surfaces, while the normal force is applied pneumatically (up to 2000 N). The three force components are measured, and the test parameters can be controlled over a wide range. The article demonstrates the feasibility of the device in several applications (especially tire materials, snow/ice surfaces) and that it can also be used to partially replace road tests with appropriate modeling and calibration. To improve road safety, Hüsemann et al. [28] also developed a mobile test rig that allows the measurement of tire characteristics on real road surfaces. Knowing tire friction contributes to improving safety and performance, and therefore, tire adhesion is at the center of tire development today. Genovese et al. [29] provide a global overview of measurement methods related to tire friction conditions.

The pressure between the friction surfaces, for example, also requires a unique friction test device in the development of deep-sea equipment. The device developed by Wu et al. [30] operates stably and accurately even under an ultra-high pressure of 80 MPa. The authors found that friction decreases with increasing pressure. Berglund et al. [31] developed a tribometer and test method for use under similar high pressures, which allows friction and wear tests to be performed at low-speed sliding, at contact pressures up to 90 MPa, in a flat-on-flat contact configuration.

Recent developments also include dedicated tribometers for measuring pre-sliding behavior at nanometer-scale displacements [32] and partial-slip hysteresis in nominally flat-on-flat contacts [33].

Nowadays, there is an increasing demand for the accurate knowledge of the friction coefficients of modern polymers (or polymer–other material pairs). Therefore, several friction meters based on the above principle but adapted to polymers have been developed [34]. Murtagh et al. [35] developed a pull-out/pull through device, and Gorczyca-Cole et al. [36] developed a device based on this, where a metal plate was pulled out of composite or polymer layers, where temperature, pressure and pulling speed were variable. The test by Vanclooster et al. [37] uses actively heated and cooled pressure plates, whose pressure can be adjusted with a pneumatic cylinder, allowing tests with precisely a controlled temperature and pressure. Similarly, Akkerman et al. [38] pull the laminate between two temperature-controlled pressure plates. The distance between the sheets is measured at four points by sensors with micrometer accuracy. More recently, Campos et al. [39] investigated interlaminar friction in thermoplastic composites using horizontal pull-out tests at different temperatures, pressures, and pulling rates.

Although there are several tables containing friction coefficients between pairs of materials used in industry, and they can be used as a first approximation, in industrial design there is an increasing need for the knowledge of precisely defined friction conditions recorded under different speed and different load parameters. Access to such universal equipment is limited in modern metrology [40]; therefore, in this article, we describe a new friction-measuring device (patent pending) [41]. Its advantage is that it can be adapted to a tensile tester, and it can either be used with the measuring system of the tensile tester or it can be operated with its own measuring system. It is a so-called mid-scale friction-measuring device (test specimen size $18 \times 18 \times 170$ mm, sample size max. $\varnothing 15$ mm, maximum surface pressure, $p_{max} = 50$ MPa). In this case, it is integrated into a modern INSTRON 68TM-30 tensile tester.

2. Materials and Methods

A Presentation of the Device

The device provides the same compressive force between the test piece and the samples clamped to it, even if the size or shape of the samples or the test piece changes slightly. The operating principle of the device is shown in Figure 3.

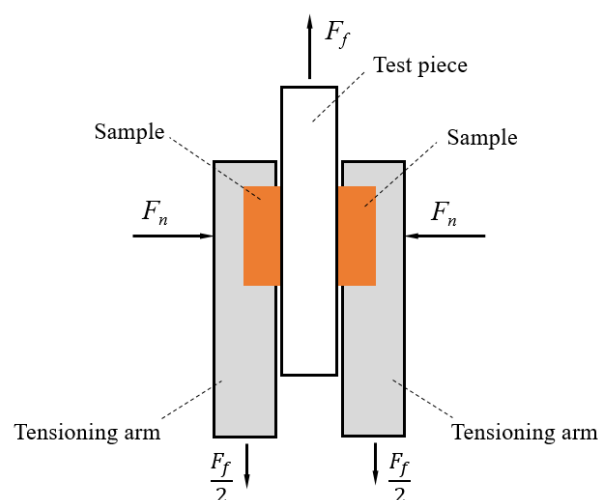


Figure 3. The operating principle of the friction-measuring device (F_f —friction force, N; F_n —normal (clamping) force, N).

In the measurement arrangement, a sample is placed symmetrically on both sides of the test specimen, therefore the tensile force registered by the tensile tester can be interpreted as the sum of the frictional forces arising on the two contacting surfaces. Accordingly, the frictional force on one contacting surface is half of the measured tensile force.

When the friction coefficient is calculated, the friction force per side must therefore be used with the normal force on that side:

$$\mu = \frac{F_{\text{friction}}}{2 \cdot F_n} \quad (3)$$

An important aspect in the design of the friction meter was that the tensile force acting on the test specimen should not affect the compressive force between the samples and the test specimen. The compensation unit ensures that the device can compensate for any parallelism error of the surfaces of the test specimen. Compared to known solutions, we took into account some basic requirements during the design of the friction-measuring device:

- The two samples must be inserted into two tensioning arms pressed together, which allow rotation but in a self-aligning way.
- The axis of rotation of the two tensioning arms falls on the planes defined by the contact between the test specimen and the samples; therefore, during measurement, the tensile force does not create a torque (and consequently no force component) that would alter the compressive force created between the test specimen and the samples.
- The samples must be placed in self-aligning sample mounts that rotate relative to the tension rods, and the center of rotation of the sample mounts falls on the contact surface of the specimen and the samples, so that the surfaces of the samples and the specimens are compressed in parallel. As a result, the surface of the samples is loaded evenly, and no torque and consequently no force component is generated under the effect of the tensile force that would change the compressive force between the specimen and the samples.

The friction-measuring device designed after strength design and finite element testing is shown in its open state in Figure 4 and in its closed state, i.e., in the arrangement during measurement (in cross-section), in Figure 5.

The friction-measuring device shown in Figures 4 and 5 can be connected to the lower stationary part of the tensile machine via the pull frame 7. The samples 1a and 1b are clamped to the test specimen 2. The samples 1a and 1b are seated in sample holders 3a and 3b, which are connected to the sample mounts 4a and 4b via vertical pins 9. The sample mounts 4a and 4b are connected to the tensioning arms 5a and 5b via pin 10 and the rotation axis of pin 10 is on the common surfaces of the samples 1a and 1b and the test specimen 2. The sample mounts 4a and 4b are pressed by the tensioning arms 5a and 5b towards the test specimen 2, i.e., towards each other. A spring- and motor-driven tensioning mechanism 6 is connected to the tensioning arms 5a and 5b. The tensioning device 6 consists of the threaded spindle 15, as well as adjustment knob and counterweight 12, with which the desired load and the equilibrium state of the tensioning device 6, and thus the entire device, can be adjusted. The desired load can be adjusted with the load cell 14. The tensioning arms 5a and 5b are connected to the tensioning frame 7 in a manner allowing rotation through the pins 8a and 8b. Additional pins 8c and 8d are put in the axis line of the pins 8a and 8b, so the tensioning arm 5a rotates around the pins 8a and 8c, while the tensioning arm 5b rotates around the pins 8b and 8d relative to the pull frame. In this way, it can be ensured that the rotation axes of pin 10 of the sample mounts 4a and 4b connected to the tensioning arms 5a and 5b are on the planes defined by the contact surfaces of the test specimen 2 and the samples 1a and 1b, while the loading of the structure remains symmetrical. During the measurement, with the clamp screwed into the test specimen 2, the tensile machine

moves away from the pulling frame 7 and pulls the test specimen between the samples 1a and 1b clamped to the test specimen. The design of the device, shown in Figures 4 and 5, allows the samples to be pressed against the test specimen with a larger surface load in accordance with the ratio of the resulting force levers. In addition, the compact dimensions of the structure allow a smaller tensile machine to be used as a measuring machine. After the measurement is completed, the release of the pins numbered 8 allows the tensioning arms 5a and 5b to be unfolded, and after the test specimen 2 is pulled out, the samples 1a and 1b can be replaced.

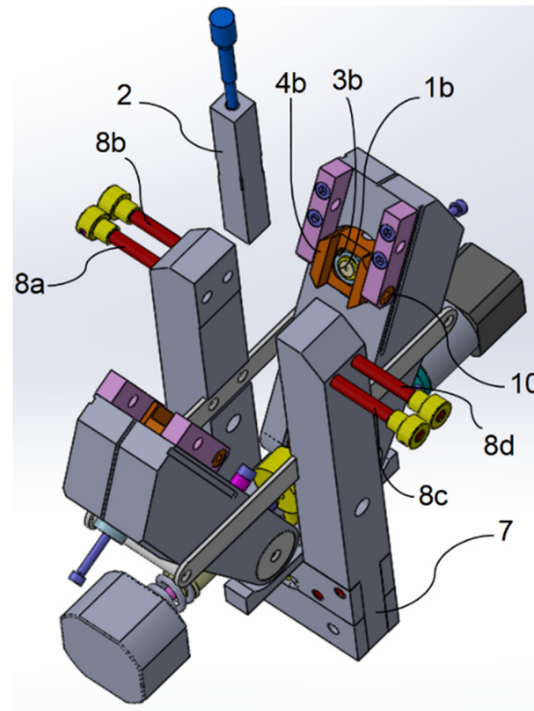


Figure 4. 3D model of friction-measuring device (open state).

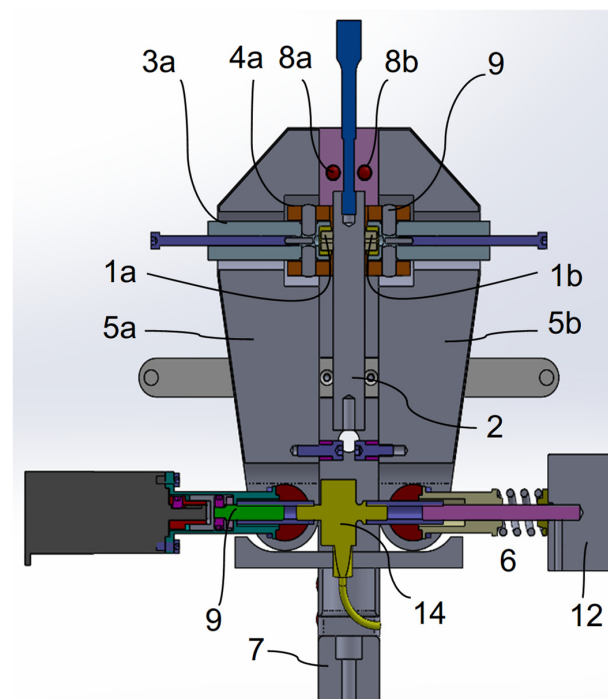


Figure 5. Cross-section of friction-measuring device (during measurement).

The overall dimensions of the structure in Figures 4–6 are $344 \times 205 \times 430$ mm. The surface areas of the two sample sizes that can be used are 178 mm^2 for a $\varnothing 15$ mm sample and 78.5 mm^2 for a $\varnothing 10$ mm sample. However, after appropriate sample preparation, individual samples smaller than $\varnothing 15$ mm can also be used. The maximum loading force (F_n) is 5000 N, which is controlled with an accuracy of ± 6 N over the entire load range. The maximum measurement data acquisition frequency is 1 kHz (which is justified by the need for the precise description of the transition between the dynamic and static friction coefficient).



Figure 6. The friction-measuring device mounted on an Instron 68TM-30 universal testing machine.

The friction-measuring device is integrated into a modern Instron 68TM-30 universal material testing machine (Instron, Norwood, MA, USA), whose parameters determine the further test parameter range. In this case, the nominal force capacity of the Instron 68TM-30 material testing machine is 30 kN, and its crosshead speed range is 0.001–1016 mm/min. The position control resolution of the machine, depending on the version, is 2.57–2.82 nm, while the accuracy of crosshead position display in the unloaded state is ± 0.01 mm or $\pm 0.05\%$ of the displayed value, whichever is greater. Crosshead position repeatability is ± 0.015 mm, and test speed accuracy in the steady state, without load, is $\pm 0.1\%$ of the set speed. The measurement system provides a data acquisition frequency of up to 5 kHz on the force and displacement channels. The accuracy of force measurement is $\pm 0.5\%$ of the measured value, up to 1/1000 of cell capacity.

3. Results

The practical applicability of the device is proven by the fact that in our previous studies, we were able to quantitatively describe the effect of sliding velocity and surface pressure on static and dynamic friction in the case of a polypropylene homopolymer (PPH) and diamond-like carbon (DLC) material pair using the same measurement platform [42], and we also performed the same measurement series and evaluation for an Al 6082-T6 and polypropylene (PP) surface pair [43]. On the other hand, with the studies performed with this measuring device, we were able to detect the asymmetric change in surface roughness and the bidirectional material transfer in the PPH–steel system [44].

Based on the above, the device we developed is suitable not only for friction force measurement, but also for the reliable investigation of complex tribological processes. Below, we present some basic measurement results that demonstrate the sensitivity and usability of the friction-measuring device.

Figure 7 shows a classical friction diagram measured with the friction-measuring device as a function of displacement for the C45 and PPH surface pair. The friction function was recorded after run-in (forty consecutive measurements), so a layer resulting from transient friction had probably already formed [44]. The choice of 40 running-in cycles was based on our previous experimental experience, which showed that friction behavior generally became stable after about this number of cycles under the tested conditions. The role of transfer layers in the friction behavior of polymer composites against steel is also discussed by Tóth et al. [45]. The initial, almost linear section of the function characterizes the state before the start of relative displacement, then the friction coefficient reaches its maximum, from which the static friction coefficient can be determined. After reaching the maximum, the force decreases to a smaller extent and then settles to a nearly steady value. This section characterizes the established sliding state, from which the dynamic friction coefficient can be determined. The diagram clearly illustrates that the device is suitable for a detailed, separate examination of the static friction maximum, the transient section and the steady sliding range.

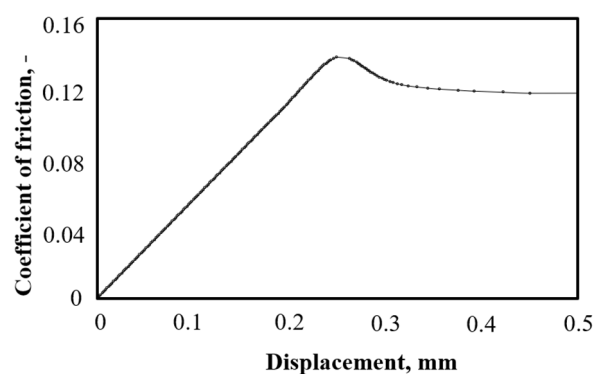


Figure 7. Frictional relations of C45 steel and PPH (surface pressure $p = 15$ MPa, sliding velocity $v = 50$ mm/min).

Figures 8 and 9 show the results obtained at different speeds and different surface pressures. Figure 8 shows the friction functions obtained at two different sliding velocities ($v = 5$ mm/min and $v = 50$ mm/min) at the same surface pressure of 5 MPa. In both measurements, we can clearly distinguish the initial force build-up phase, the vicinity of the static friction maximum, and the steady-state sliding range. The course of the two functions is similar, but the differences in the diagram show that the device sensitively follows the changes resulting from sliding velocity.

Figure 9 shows the coefficient of friction as a function of displacement at two different contact pressures (5 MPa and 15 MPa) at the same sliding velocity of 50 mm/min. The diagram also clearly shows the static and dynamic friction ranges. The curve of the function measured at higher surface pressure differs only slightly from the result at lower pressure, which indicates that the effect of surface pressure is moderate in this test range for the given material pair. At the same time, the measurement results demonstrate that the equipment is suitable for comparative friction tests performed under different normal loads.

Table 1 presents the results of three repeated friction tests. For each test, the dynamic friction coefficient (μ_{dyn}) was determined at four different positions within the steady-state sliding region, while the static friction coefficient (μ_0) was determined from the maximum

friction force. The tests were performed over a sliding distance of 80 mm at a sliding velocity of 5 mm/min and a nominal contact pressure of 15 MPa.

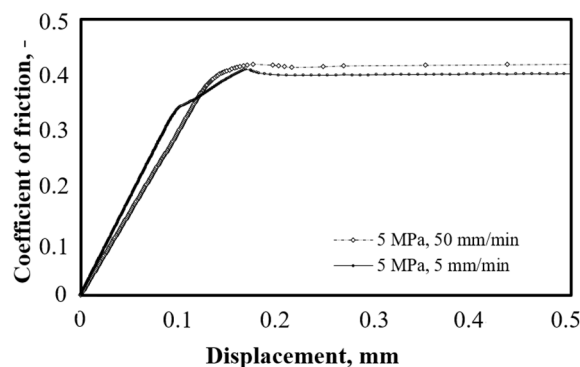


Figure 8. Effect of sliding velocity on friction for the C45 and PPH material pair ($p = 5$ MPa).

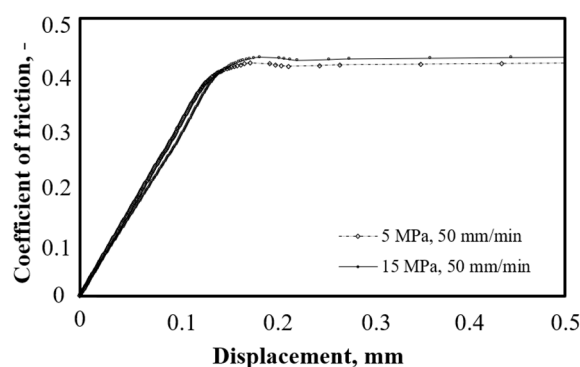


Figure 9. Effect of surface pressure on friction for the C45 and PPH material pair ($v = 50$ mm/min).

Table 1. Static (μ_0) and dynamic (μ_{dyn}) friction coefficients obtained repeated tests ($v = 5$ mm/min; $p = 15$ MPa; sliding distance: 80 mm).

Measurement Point	μ_{dyn}	μ_0
1	0.1982	0.2318
2	0.1965	
3	0.1977	
4	0.1969	
5	0.1960	0.2326
6	0.1969	
7	0.1967	
8	0.1973	
9	0.1948	0.2343
10	0.1965	
11	0.1956	
12	0.1960	
Average	0.1966	0.2329
Standard deviation	0.0009	0.0013

The mean static friction coefficient was 0.2329, with a standard deviation of 0.0013 across the three repeated tests. For the twelve dynamic friction values, the mean was 0.1966

and the standard deviation was 0.0009. In both cases, the relative standard deviation was below 0.6%, indicating low deviation under the investigated conditions.

4. Discussion

Previous studies have already demonstrated that plane-to-plane friction measurements can be performed using tensile or servo-hydraulic testing machines and that pull-through arrangements can be used to control normal load, sliding velocity and, in some cases, temperature [19,20,31,34–38]. Therefore, neither adaptation to a material testing machine nor the use of a flat-on-flat contact configuration should be considered novel in isolation. The methodological contribution of the present device lies in the combination of a symmetric, two-sided contact configuration, a closed loading system and a two-stage self-aligning mechanism designed to reduce the coupling between the imposed normal load and the tensile force used to determine friction.

The two tensioning arms 5a and 5b rotate about the coaxial pins 8a–8d, while the sample mounts 4a and 4b rotate relative to the tensioning arms about pin 10, as shown in Figures 4 and 5. The corresponding axes of rotation are positioned in the planes defined by the two contact interfaces. Consequently, in the ideal geometric configuration, the tangential force has no effective lever arm about these axes, and the resulting parasitic moments are minimized. The sample holders 3a and 3b can additionally rotate about the vertical pin 9, allowing the samples to accommodate small angular deviations, parallelism errors and asymmetric elastic deformation.

This arrangement is particularly relevant at elevated nominal contact pressures, where small eccentricities or angular deviations may produce pronounced local pressure gradients. In rigid pull-through or plane-to-plane fixtures, such deviations may couple the tangential loading to the applied normal load and thereby influence the measured friction force [19,20,31,34–38]. In the present design, passive rotation at both the tensioning-arm and sample-holder levels is intended to maintain more uniform normal loading while the specimen is pulled. Accordingly, the novelty of the device is best interpreted as a load-path and alignment solution rather than simply as an additional friction fixture for a universal testing machine.

The mechanical advantage of the closed loading system also enables elevated nominal contact pressures to be applied to medium-sized flat samples. For a sample diameter of 15 mm and a nominal contact area of approximately 178 mm², a normal load of 5000 N corresponds to a nominal contact pressure of approximately 28 MPa. When samples with a diameter of 10 mm are used, the declared maximum nominal contact pressure of 50 MPa is reached at a normal load of approximately 3.93 kN.

Figure 10 compares the developed UTM-adaptable two-sided flat-on-flat friction device with selected published friction-test systems and reference configurations in terms of maximum reported normal load and minimum nominal contact area. With a maximum normal load of 5 kN and a minimum nominal contact area of 78.5 mm², the developed device occupies an intermediate operating range between conventional pin-based tribometers and large linear or flat-on-flat test rigs. This combination enables flat-on-flat friction measurements at elevated nominal contact pressures on engineering-scale specimens while retaining the compactness and adaptability required for integration into a universal testing machine.

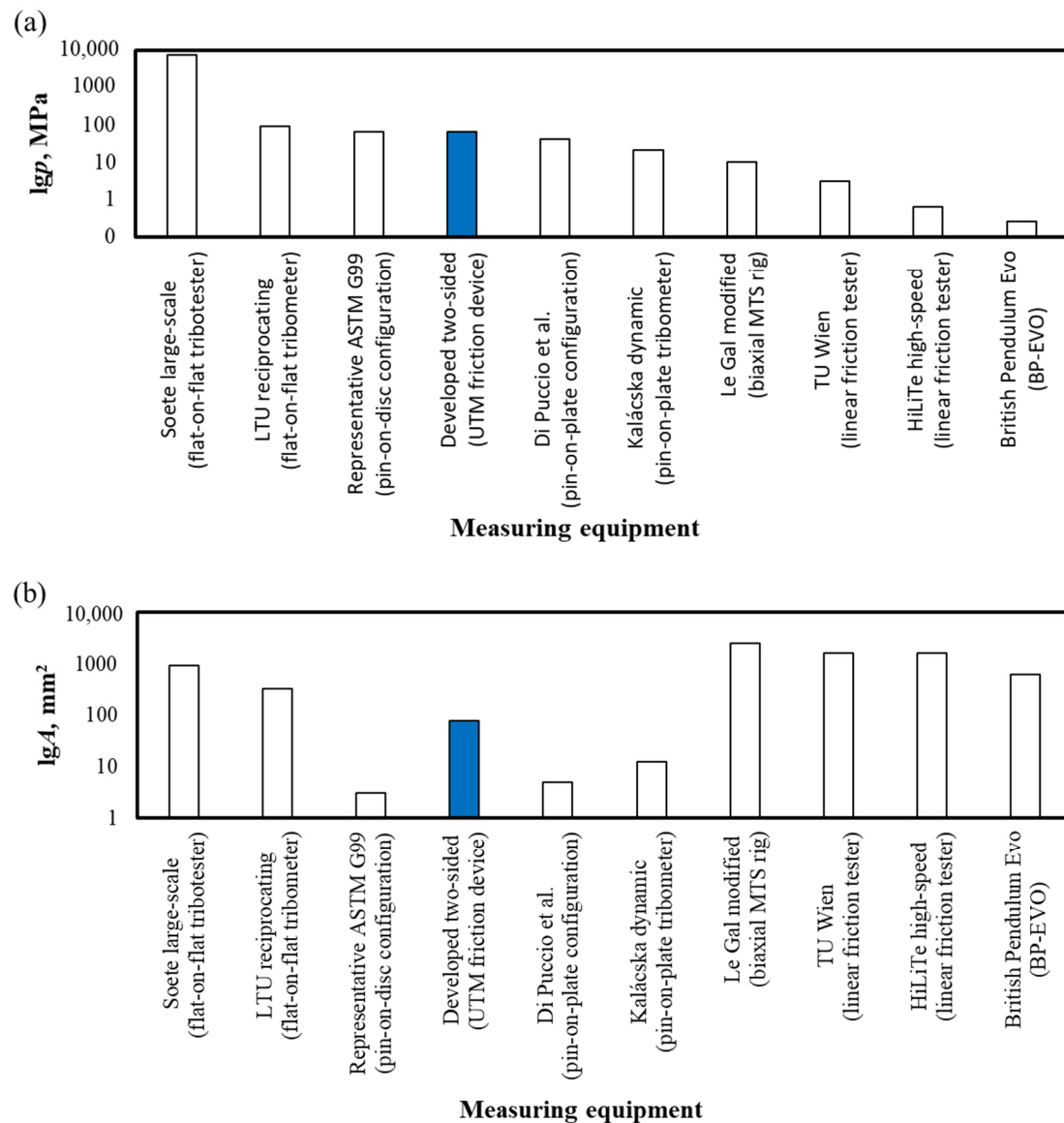


Figure 10. Comparison of selected friction-test systems and reference configurations in terms of (a) maximum reported normal load and (b) minimum nominal contact area. The plotted values represent reported device limits or literature-based reference conditions, as applicable. The vertical axes in both panels are logarithmically scaled. The developed UTM-adaptable two-sided flat-on-flat friction device presented in this work is highlighted. (Soete large-scale (flat-on-flat tribotester) [46]; LTU reciprocating (flat-on-flat tribometer) [31]; Representative ASTM G99 (pin-on-disc configuration) [47]; Developed two-sided (UTM friction device) [41]; Di Puccio et al. (pin-on-plate configuration) [48]; Kalácska dynamic (pin-on-plate tribometer) [49]; Le Gal modified (biaxial MTS rig) [29]; TU Wien (linear friction tester) [27]; HiLiTe high-speed (linear friction tester) [50]; British Pendulum Evo (BP-EVO) [29].

Based on the presented results, the device is suitable for separating the main stages of the friction process. In the initial, pre-slip region, we can well identify the build-up of tangential force, then the static friction maximum, and finally the steady-state sliding phase [51]. This makes it possible to determine both the static and the dynamic friction coefficient from the same test. The examples presented with different sliding velocities and surface pressures should also be interpreted as demonstrative results proving the operability and sensitivity of the device.

Another advantage of the measuring system is that it can utilize the controlled displacement and force measurement capabilities of a tensile tester, and so the system can be

used as a compact additional unit. This eliminates the need for a separate, large tribometer, while retaining controlled force and displacement measurement and high data acquisition capability. The data acquisition frequency of up to 1 kHz is particularly useful for investigating the transition between static and dynamic friction, as the maximum of friction and the subsequent lower, dynamic friction occur in a short displacement range.

This article presents the principle, structural design and measurement capabilities of the friction-measuring device we developed. The presented results demonstrate that the system is suitable for comparative testing of different material pairs, surface pressures and sliding velocities. In future research, the device can be used to record detailed parameter maps, test surface-treated or coated systems and analyze surface roughness changes, and wear and material transfer in addition to friction.

5. Conclusions

In this article, we presented a new friction-measuring device that can be adapted to a tensile testing machine. The principal methodological contribution of the system is the combined use of a symmetric, two-sided flat-on-flat contact configuration, a closed loading system and two-stage self-alignment within a fixture adaptable to a universal testing machine. By positioning the relevant rotational axes in the contact planes, the arrangement is designed to minimize parasitic moments and coupling between the tensile measuring force and the applied normal load while promoting uniform loading of the samples. The resulting compact device provides a mid-scale experimental platform for determining static and dynamic friction at controlled sliding velocities and nominal contact pressures up to 50 MPa. The following conclusions can be drawn from its operation and initial measurement results:

- The equipment is suitable for determining the static and the dynamic friction coefficient, as well as for a detailed examination of transition sections, with two-sided, flat-on-flat contact.
- The equipment can be used to test specimens with a cross-section of 18×18 mm, as well as samples of $\varnothing 15$ mm or smaller samples, with a normal load of up to 5000 N.
- The demonstrative measurement results indicate that the equipment is capable of isolating the characteristic stages of the friction process: the initial force build-up, the static friction maximum, and the steady-state dynamic friction range in detail.
- The presented friction curves also demonstrate that the system is suitable for comparative testing of the effects of sliding velocity and surface pressure.

Overall, the device we developed (patent pending) can be useful research equipment for investigating the frictional relationships of metallic, polymer, coated and surface-treated material pairs, especially in cases where it is necessary to determine parameter-dependent frictional behavior under higher surface loads [41].

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