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Design and Manufacturing of a Pin on Disk Tribometer

This paper presents the design and manufacturing of a pin on disk tribometer aimed at performing friction and wear testing as accurate as a professional tribometer at a lower cost. Since friction is an important part of our lives and its application varies greatly in size, environment and other factors, testing can be expensive. Tribometers are instruments where these conditions can be simulated experimentally. They are manufactured by various companies abroad and are imported to Turkey. For this reason, the cost of these instruments is very high. The design of the manufactured tribometer prioritizes portability and low cost of manufacturing. The manufacturing process of the various parts are discussed in detail. The tribometer was manufactured in the ATILIM University manufacturing laboratories within a tight budget using CNC machining. The instrument has the full capability to adjust the load, testing radius, motor speed, and the duration of the test before starting the experiments. To handle the electronics and data gathering within the instrument, Arduino boards and software are utilized. Real-time data streaming is made possible for data analysis tasks both during and after the experiments. The paper also provides the results of experiments that are obtained from the newly developed tribometer and comparisons with a mass produced, professional tribometer. The experiments are conducted with the same type of samples and with the same parameters. The manufactured tribometer provides researchers with easily accessible friction data that is within close range to what they would get from a professional tribometer.

Keywords: Tribometer Design, Manufacturing, Tribological Test, Coefficient of Friction Measurement, Surface Characterization

1. INTRODUCTION

Tribology is the science behind friction, wear, and lubrication. Tribological tests are very important to observe the results of two surfaces interacting at many different variables like speed, temperature, time, and the presence of lubrication. The duration of the tribological experiments is a critical factor that affects the accuracy of the results. Longer test times can provide more accurate friction coefficient calculations, but the optimal test duration depends on the specific application. The test duration can usually be determined by time, laps taken during tests, or the amount of travel in meters.

Instruments used for tribological tests are tribometers. Different kinds of tribometers have been used in research, mainly being pin-on-disk, sk, oscillating, and four-ball.

The tribometer has been used in many different fields of research. In 2016, researchers proposed the design of a completely computer-controlled pin-on-disk type tribometer that measures the coefficient of friction by utilizing a three-axis piezoelectric force sensor. The performance of the proposed tribometer is demonstrated with a case study that includes the measurement of friction and wear of a dry clutch [1].

In 2020, a tribometer was used in analysing dental composite materials [2]. An artificial oral environment has been created on a pin-on-disk tribometer by using artificial saliva and adjusting the force, temperature, and speed accordingly.

There are some custom-built tribometers in universities as well. In 2021, a pin-on-disk tribometer was built at São Paulo State University [3]. The tribometer was used to measure the friction coefficient of different surfaces such as mild steel, 60-40 brass, and ferritic stainless steel. The instrument also utilizes Arduino boards for the electronic circuitry and data gathering. Some more detailed examples are further discussed.

A multi-function tribometer was designed at the University of Michigan in 2010. This tribometer was expected to perform the standard pin-on-disk, linear reciprocating test, and follow a custom 2D path for wear testing. For the linear reciprocating testing a DC servo motor was chosen and for the pin-on-disk test a DC stepper motor was chosen. An Arduino electronic interface was picked for use in the electrical components. The data collection and storage for this tribometer were done by utilizing a LabVIEW program [4].

In 2012, a custom tribometer was built with a different normal force application system. In this article, the rotation speed and the normal force are controlled with servo motors. A leaf suspension system is used in the application of the normal force to make sure the vertical axis stays stable during testing. The loading of the vertical axis was tested with and without the suspension system and the improvements of the suspension system were confirmed. After the implementation of the leaf suspension to the system, several experiments have been conducted to verify the effectiveness of the system [5].

In 2014, a tribometer was proposed to be used in research for blast furnaces off-dust. The tribometer was modified to simulate a blast furnace. The friction between the pellets and the wall/pellet friction was measured. This refinement significantly facilitated experimentation within a controlled laboratory setting [6].

A tribometer was developed to perform pin-on-disk and linear reciprocating tests at Yıldız Teknik University. An additional feature of this tribometer was that the temperature was supposed to be a controllable variable as well. This tribometer used load cells and thermocouples as sensors. The heating of the pin was done by an infrared lamp and the rotation in the system was provided by an AC servo motor [7].

In 2017, a professionally made tribometer was used to analyse the friction in a metal forming process. The forming process was analysed by FEM to adjust the test for the tribometer. After that, testing with different surface enlargement, contact pressure, and temperature was done. To check if the adjustment was made correctly, the microstructures were compared with the actual samples from real applications. In conclusion, the lubricant used made the temperature the most important variable. The coefficient of friction was found to be higher in lower temperatures because the lubricant was more viscous at lower temperatures and less viscous at higher temperatures [8].

In 2018, a pin-on-disk tribometer was used in a paper that analysed hip implant materials. According to previous data, a large amount of hip implant surgeries result in reoperation. To combat this problem, researchers have been trying different methods to improve longevity of the materials. One of the ways to improve longevity is to manufacture spherical micro-texture features on the surface. In this article, friction and wear testing is done to observe the difference in longevity between normal materials and microtextured materials [9].

In an article written by Chen et al, a tribometer was built to investigate the bushing wear in aircraft engines. To simulate the conditions of the bushings in aircraft engines, a reciprocating tribometer with temperature control was designed. Validation tests were done to confirm the data acquisition system and fixtures were acting as expected. After confirmation that the tribometer was working as intended, high-temperature testing was done on three different polyamide bushing materials and the results from these tests showed that SP2515 was the most suitable material [10].

In 2023, an open-source pin-on-disk tribometer was made. A stepper motor was used for rotation of the disk, a force sensor was used for data collection and a unique graphical user interface was developed. All the progress was documented in detail to keep in line with the project being open-sourced. To confirm that the tribometer worked as intended testing was compared to literature data and the results were satisfactory [11].

A tribometer that was patented in 2017 is a pin-on-disk tribometer with on board wear testing. The force control is done by a pneumatic cylinder and the motor selected is a servo motor for precise velocity control. As the test is running, a laser displacement measurement apparatus is used to reflect the laser from a sample to measure the displacement of the test specimen [12].

Another tribometer was patented to solve unwanted motions and factors that can reduce the accuracy of tribological measurements. The inventor claims that the instrument can accurately measure displacement while eliminating the waving motion on the disk, the thermal expansion of the device, and other factors that can badly affect the accuracy of the measurements. The patent focuses on solving some of the issues related to wear measuring with displacement sensors mounted at the base of the rotating part and removing the specimen and weighing it to get the wear data. The inventor claims that these methods are not reliable enough. This patent is about the solution to this problem and to solve this issue, the displacement sensor is mounted on the pin [13].

The manufactured tribometer in this paper utilizes the pin-on-disk method. A tribometer that is portable, light, and competitive in terms of price is designed and manufactured. It also uses software that allows researchers to get real-time coefficient of friction data that can be processed both during and after the test is done. During the test, a real time coefficient of friction time graph can be drawn and mean, minimum, and maximum values can be obtained. The tribometer that is proposed ultimately aims to provide researchers with a portable and price-competitive instrument for tribological tests while allowing them to access the most accurate data possible to output with minimal effort. There are few pin-on-disk tribometers in the literature that are truly portable. A benefit of the tribometer being portable is that it can be used in school/industry projects where people can use it by carrying it around in between tests. As the tribometer allows real-time data streaming, it also makes it possible to run data science projects on it as well. Students and researchers can further customize the parameters to conduct unique research. The developed prototype uses the same pin-on-disk principles as the professional tribometer taken as a reference. The main differences are portability, low cost, and capacity for future expansions. The manufactured tribometer additionally offers an easy to use and customizable interface thanks to the open-source platform of Arduino while the reference tribometer uses a proprietary software that has a certain learning curve.

The motivation of this project includes, designing and manufacturing of a new portable tribometer at low cost to serve industry and university. It can be expanded to conduct high temperature friction tests by only adding a heater. Software used does not require a license and is available on most computers. In the current design, a load cell is used instead of strain gauges to provide more accurate data. The motivation of the project can be summarized as to develop a low cost and a portable pin-on-disk tribometer which can be used in educational/research environment.

2. DESIGN REQUIREMENTS

The manufactured tribometer can conduct experiments with 6mm Alumina (Al_2O_3) or 100Cr6 steel balls integrated into the pin. Different external loads can also be used with the tribometer. A maximum of 10N and a minimum of 1N external loads can be used. The verifications of the manufactured loads are done using precise calibration weights. Finally, the linear speed of the motor should be a maximum of 1400 mm/s and the related design calculations are done considering these requirements. The table related to the design requirements of the manufactured tribometer is given in Table 1.

Table 1. Design requirements

Specification	**Value**
Alumina or Steel Ball Diameter **[mm]**	6
Normal Load **[N]**	1-10
Linear Speed **[mm/s]**	0-1400

The proposed instrument is designed to adhere to the ASTM G99 and G115 standards. The main points in G99 are that the motor needs to be able to adjust the speed while being able to maintain a constant one and the tolerance of the angle between the specimen and the pin needs to be ± 1° [14]. G115 generally talks about the test procedure and specimen preparation [15].

3. DESIGN & DRAWINGS

Since one of the aims of the instrument is to be light, the design is kept as small and portable as possible. The overall design and the cross section view of the pin-on-disk tribometer is shown in Figures 1 and 2 respectively. The design includes the upper part of the instrument where the main upper arm, external load, substrate, counterweight, linear bearing assembly, sample holder, and the leadscrew are located. The upper part sits on top of the top plate. The step motor is located in between the two plates and a motor sleeve is specifically manufactured to house it.

The upper arm is the most important piece in the design and the technical drawings of the upper arm can be seen in Figures 3, 4, and 5. This part is designed to be lightweight and accommodate all external parts attached to it. Since the loads involved in the project are relatively small, weight reduction is achieved by using aluminium 6061 material and a hollow square profile. The assembly of this part also posed some significance as well. However, the movement of the part could create friction and affect the results. To counter this, the pin is fitted to the upper arm and also to two of the ball bearings mounted on the pin connection part.

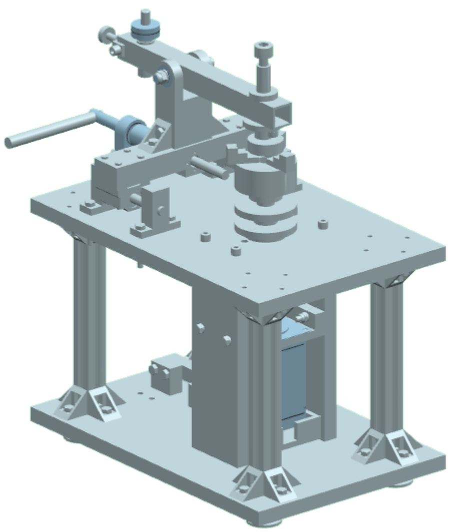


Figure 1. Isometric view of the manufactured tribometer

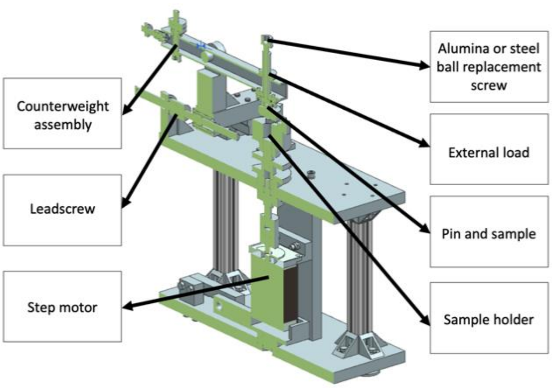


Figure 2. Cross section view of the manufactured tribometer

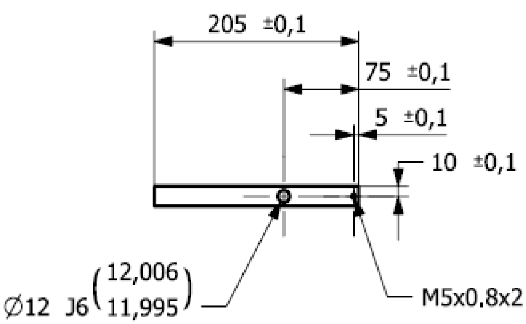


Figure 3. Upper arm top technical drawing

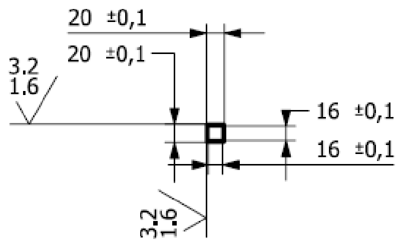


Figure 4. Upper arm side technical drawing

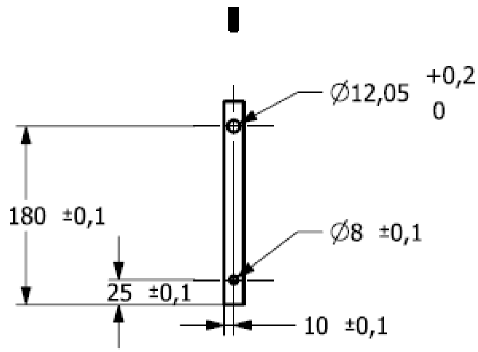


Figure 5. Upper arm bottom technical drawing

The sliding plate is designed to control the upper arm assembly’s position. The purpose of this part is to be the connection for the upper arm assembly and the linear bearings to control the test radius. The design of this part is mainly affected by material availability at the time. Aluminium 6061 material is selected to reduce weight and the part is designed to be fitting with default linear bearings. The technical drawing of the part can be seen in Figure 6.

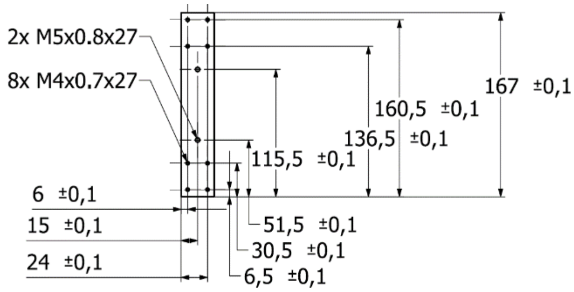


Figure 6. Sliding plate technical drawing

The third part featured is the plates. The plates are designed to carry the whole assembly. Calculations are done using Finite Element Method. The plate thickness is determined to provide the necessary stiffnes as 30mm and the material is aluminium 6061 for both the upper and lower plates. All of the mounting holes for the other components that are bolted or fitted on the plate are manually measured and integrated into the design. The technical drawing of the lower plate can be seen in Figure 7.

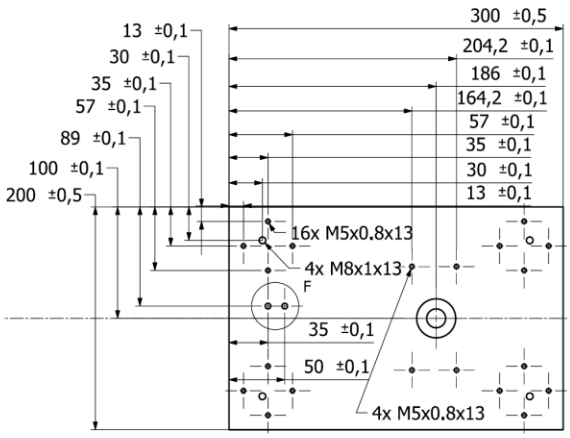


Figure 7. Lower plate technical drawing

Finally, the rotating part is designed to transfer the rotation from the step motor to the specimen holder. This part is also made longer than required to leave space for a temperature control system to be integrated in the future if desired. Since this part is under load during testing, stainless 304 steel is picked as the material of choice to assure structural integrity. The part can be seen in Figure 8.

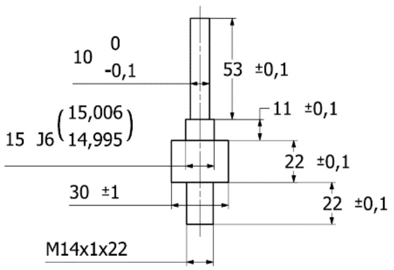


Figure 8. Rotating part technical drawing

4. DESIGN CALCULATIONS

4.1 Power calculation

Calculations according to a maximum of 1400 mm/s linear speed are done and the minimum power required for the motor selection is found.

$$\omega = 93.333\ rad / s \qquad (1)$$

$$T = f\,x\,r = 10\ x\ 15 = 0.15\ N \cdot m \qquad (2)$$

$$P = T\ x\ \omega = 0.15\ x\ 93.333 = 14\ W \qquad (3)$$

$$mm/s\ to\ rpm = (1.4\ x\ 60) / (2\ x\ \pi\ x\ 0.015) = 891.267\ rpm \qquad (4)$$

In equation (1), ω represents angular velocity which is measured in radians per second. In the equation (2), T denotes torque which is calculated by multiplying force (f) by the radius of the rotating part (r). In equation (3), P represents the power of the motor which is calculated by multiplying torque and angular velocity. Finally in equation (4) linear speed is converted from millimeters per second to rounds per minute. Figure 8 shows the free body diagram of the rotating part.

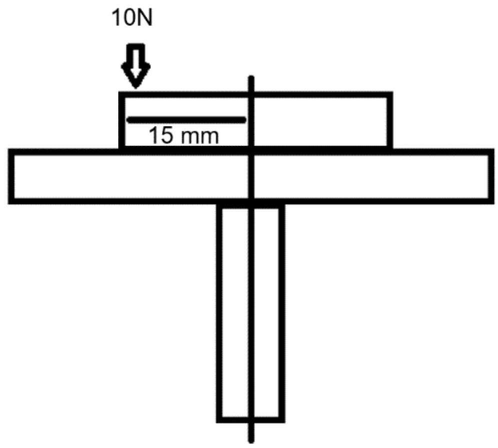


Figure 9. Free body diagram of the rotating part

4.2 Arm design

The arm design is done by checking how much the counterweight needs to be according to the dimensions already selected and whether the arm would yield or not. The free body diagram of the upper arm is shown in Figure 10. Using the values from the diagram, the largest moment in the system was found to be 32.3625 N·mm.

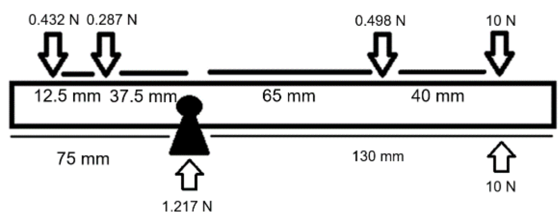


Figure 10. Free body diagram of the upper arm

$$I = ((b_o\ x\ h_o^3) - (b_i\ x\ h_i^3)) \div 12$$
$$I = ((20\ x\ 20^3) - (16\ x\ 16^3)) \div 12 \qquad (5)$$
$$I = 7872\ mm^4$$

$$S = (M \times c) \div I = (32.3625 \times 10) / 7872 = 0.04\ N / mm^2\ (MPa) \tag{6}$$

In the equation (5), I denotes moment of inertia, b_o is the outer width of the arm, h_o is the outer height of the arm, b_i is the inner width of the arm, h_i is the inner height of the arm. In the equation (6), S is the section modulus, M is the applied moment and c is the distance from the neutral axis to the outermost part. Since S_y = 276 MPa is larger than 0.04 MPa, it is known that the upper arm will stay in the elastic range.

5. ELECTRONICS COMPONENTS & MODULES

Since data needs to be collected and the speed of the motor needs to be adjusted, electrical components are added. A step motor, step driver, power supply, load cell and two Arduino cards are chosen to be added to the tribometer to satisfy these requirements.

The chosen step motor is a Nema 23 2.2 N.m Step motor, the driver is a tb6600 step motor driver, and the power supply is a 24 VDC power supply. These components are chosen to satisfy the speed requirements. The load cell is chosen as a 1kg load cell to collect the data. Two Arduino UNO's are used because the delay in the load cell code interrupts the step motor code which results in inconsistencies in the motor speed. Using two boards helps alleviate this issue.

The setup of the two circuits can be observed in Figure 11 and Figure 12.

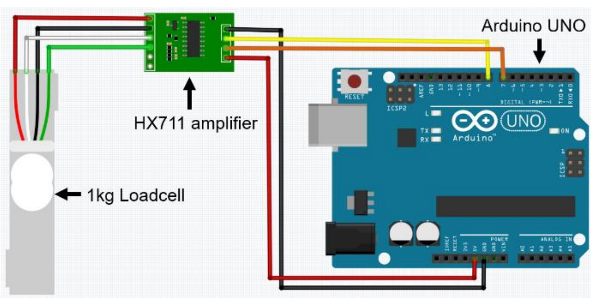


Figure 11. Wiring of the load cell circuit

The motor is used to control the speed and the load cell is used to get a force value to calculate the torque. Finally, the general setup of the two Arduino boards, power supply, amplifier and motor driver are presented in Figure 13.

6. WORKING PRINCIPLE

The tribometer design prioritizes ease of use. The tribometer aims to simulate sliding or rolling motions in an experimental way by conducting contact and relative motion between two surfaces being, a pin and a rotating disk. The sample is cleaned and prepared according to the researcher's needs. The top pin comes into contact vertically with the disk before applying an external load. The loads can be adjusted to suit the requirements of the experiment up to 10N. 6mm alumina (Al_2O_3) or 100Cr6 steel balls can be integrated into the pin for conducting experiments. As the disk connected to the motor begins to rotate, friction forces are generated between the ball on the pin and the surface of the sample. These friction forces then lead to wear on top of the sample which can be seen by the naked eye. As the instrument is being operated, Arduino boards stream data to the connected computer to record force data from the load cell at the rate that is chosen beforehand. With this data, the researcher can draw the real-time coefficient of friction graph and manipulate the data according to their needs. After the test is finished, further data processing tasks can be handled or the sample can be further analysed using different methods such as optical microscopy, scanning electron microscopy, or surface profilometry. These analyses could be helpful in finding out more about how the wear mechanisms and surface changes caused by the tribological testing affected the surface of the sample. Additionally, these tasks done after the tests can help optimize the parameters of the tribological experiments as the researcher would gain deeper knowledge about the surface that they are working with and how each parameter affects it.

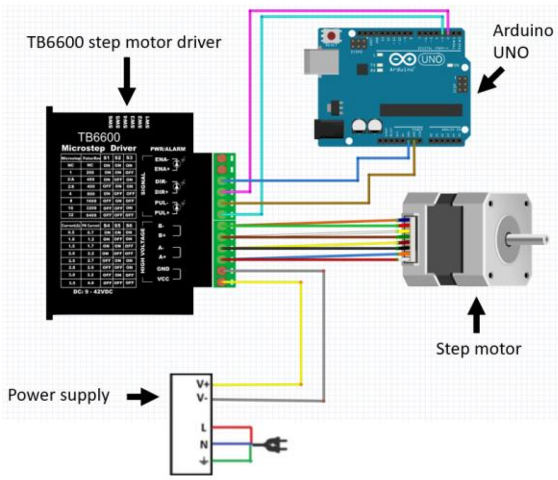


Figure 12. Wiring of the step motor circuit

The motor casing itself is not bolted down but centred with ball and conical bearings. In this setup, the motor is mounted in a motor sleeve and the arm of the motor sleeve contacts the load cell to output a force value. Since the distance from the centre of rotation is predetermined, the coefficient of friction is calculated from the force value.

The visualization of the process can be seen in Figure 14.

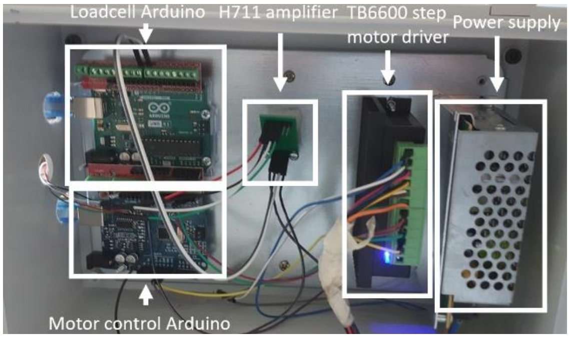


Figure 13. Final electronics assembly

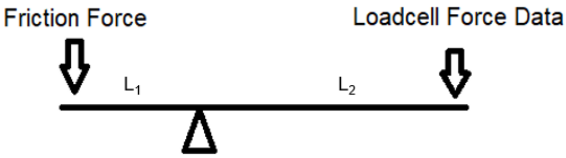


Figure 14. Working principle free body diagram

The centre of rotation is the pin connection in the free body diagram, L_1 is the specimen test radius and L_2 is the distance between the centre of rotation and the contact point of the load cell. The program starts by reading the load cell voltage. The load cell voltage is then converted to force which equals to the friction force. Since the applied external load is known before hand, it is entered by the user as the normal force. Finally, the coefficient of friction is found by dividing the friction force by the normal force. The equation of the coefficient of friction is given.

$$\mu = \frac{F_{friction}}{F_{normal}} \tag{7}$$

In the equation (7), the coefficient of friction is represented with μ, friction force is represented with $F_{friction}$ and finally the normal force is represented with F_{normal}.

7. MANUFACTURING

The parts were manufactured in ATILIM University manufacturing laboratories. A lathe and a CNC machine are used to manufacture most of the parts needed. The manufacturing steps taken, and the purpose of the key parts are discussed further.

The manufacturing of the top plate starts with the cutting of a long plate of material into a smaller plate with a horizontal bandsaw. After that, the CNC machine is used to get the measurements as close as possible to the actual measurements. Then, the marks for the holes are made and the bearing hole is formed. Finally, a vertical drill is used to manually drill the holes through the material and a tap is used to create the threads afterwards.

Since the motor sleeve is a crucial part of this instrument's working principle, the part design could not be changed as much as the other parts. This part is completely manufactured in the CNC machine because of part complexity and the lack of a manual milling machine. The motor sleeve can be observed in Figure 15.

Figure 15. Motor sleeve

The sliding part was designed to be an assembly part between the upper arm and the linear bearings. Since it must be assembled with many default parts, most of the manufacturing is done in the CNC machine to make sure the threaded holes line up. The sliding part can be observed in Figure 16.

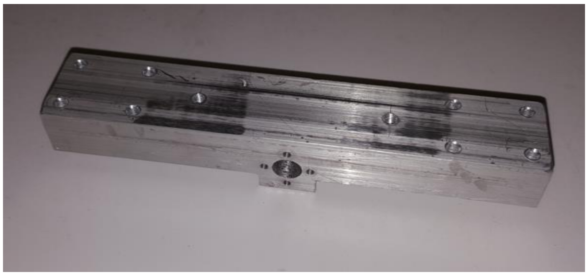


Figure 16. Sliding part

The sample holder can house samples that are circular, and it allows a maximum diameter of 35mm. It can be adjusted to lock in smaller sized samples. The sample holder has a rotating locking mechanism where the holder gets tighter as it is rotated counterclockwise. This feature is essential for working with a variety of sample sizes. It is particularly important to make sure the sample is tightly locked in during experiments. An unlocked sample could lead to fluctuations during tests which can result in, damage to the sample and the pin, inconsistent friction results, safety concerns and potentially incomplete data. The 1050 steel sample holder can be observed in Figure 17.

Figure 17. Sample holder

The section that houses the main upper arm, load, sample, counterweight, linear bearing assembly, sample holder, the leadscrew, and the aluminium or steel ball replacement screw can be observed in Figure 18.

After manufacturing, assembly is done with all the default parts and the manufactured parts fitting together. The final assembly can be observed in Figure 19. The individual parts that make up the assembly are also labelled accordingly.

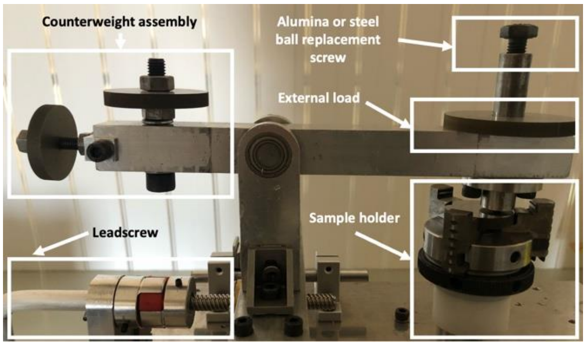


Figure 18. Upper part of the tribometer

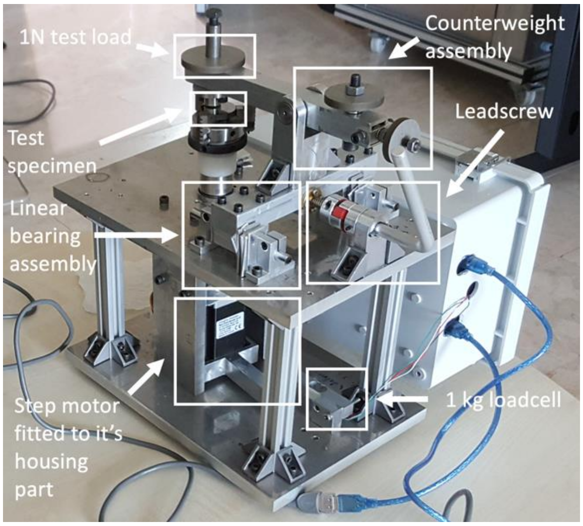


Figure 19. Isometric view of the final assembly

8. TESTING

Testing is done following the proper procedures being; cleaning the surface of the sample, making sure the upper arm is correctly operated and setting the correct parameters within the software. To confirm that the tribometer is working according to the set standards, a reference test is conducted with the CSM tribometer in the Metal Forming Center of Excellence. The parameters, incuding samples and pins used in all tests are the same among all the tests that are conducted. This reference test is used to evaluate the validity of the data outputted from the manufactured tribometer. The specifications of the CSM tribometer is presented in Table 2, while the general view can be observed in Figure 20.

The reference test is done on a CSM tribometer with a D2 steel substrate as the sample. Circular samples are cut from steel rods in dimensions of 30 mm radius and 5-7 mm thickness. Heat treatment is then applied to the circular samples before sanding, polishing and ultrasonic cleaning sequentially. Finally, the surface of the sample is cleaned and prepared with precision wipes for optimal testing. D2 steel is a high carbon and high chromium tool steel with high wear resistance, toughness and hardness. This makes it especially good for tribological tests. The wear marks left on the samples after testing can be seen in Figure 21 for comparison. 6mm alumina (Al_2O_3) or steel 100Cr6 balls can be used within the tribometer pin. Alumina or steel ball replacement screw is first unscrewed then the ball is placed into the pin before finally screwing the screw. The tests are done using steel 100Cr6 6mm balls integrated into the pin. Alumina balls are generally harder than steel balls with higher resistance to deformation and wear. That is why they are preferred while testing samples with harder surfaces. Steel balls are preferred in cases where cost is an important factor, as they are comparatively more affordable than their alumina counterparts. Because the samples are of D2 steel material, steel 100Cr6 balls are deemed suitable to be used for testing, as there are no compatibility issues between these two materials. These can also be seen in Figure 22.

Figure 21. Wear marks on the D2 steel sample after testing with the (a): manufactured tribometer, (b): CSM tribometer

Table 2. Specifications of the CSM tribometer

Sensors	
Type	**Range**
Normal Load **[N]**	Up to 10
Friction Load **[N]**	10
Pin-on-Disk: Speed **[rpm]**	500
Measurement Performance	
Type	**Max**
Linear: Speed **[mm/s]**	100
Linear: Stroke Length **[mm]**	60

The same test with the same sample, ball and parameters has been conducted using both tribometers and the results are plotted in the same graph in order to make a better comparison. The test parameters are as follows; The radius of track is 7.5 mm, the speed is 100 mm/s and the external load is 1 N. The test is run for 8 minutes and 20 seconds. The manufactured tribometer is designed for room temperature applications, so the temperature is not directly controlled. The manufactured tribometer does not possess a thermocouple to conduct temperature measurements and all experiments are conducted at room temperature. The CSM tribometer used as a reference did not come with a built in thermocouple but the authors have integrated a thermocouple in the recent years to take temperature measurements as needed using the CSM tribometer. Since the temperature fluctuations are low and insignificant during room temperature tests, the friction coefficient results are not affected. A thermocouple sensor could be added to the manufactured tribometer in future to improve the capabilities of the system. The results from the test can be seen in Figure 23. It is seen that the curves for coefficient of friction in both experiments are similar. The y axis shows the coefficient of friction value while the x axis shows the time in seconds. The minimum, maximum and mean coefficient of friction values outputted from each tribometer is shown in Table 3.

Figure 20. General view of the CSM tribometer

Figure 22. (a): Alumina (Al_2O_3), (b): 100Cr6 steel 6mm balls

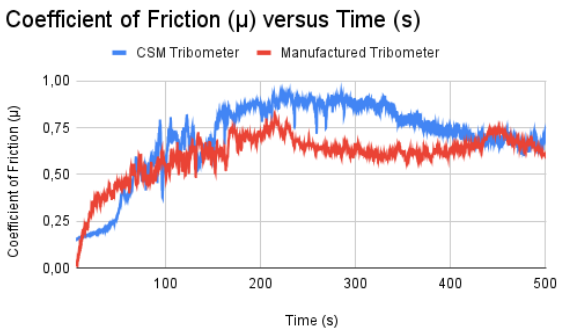


Figure 23. Coefficient of friction versus time comparison between the CSM tribometer and the manufactured tribometer

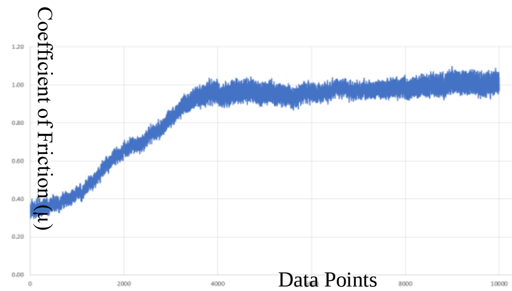
Table 3. Comparison test results

µ	Min	Max	Mean
CSM Tribometer	0.129	0.924	0.686
Manufactured Tribometer	0.006	0.818	0.603

The CSM tribometer outputs a mean coefficient of friction value of 0.686 while the manufactured tribometer outputs a mean coefficient of friction value of 0.603. When compared, the similarities in the curve characteristics can be observed. While comparing the mean values, a less than ±0.1 difference can be observed, which is deemed acceptable for friction results. The reliability of the manufactured tribometer is tested with around ±10% variance when compared to the CSM tribometer.

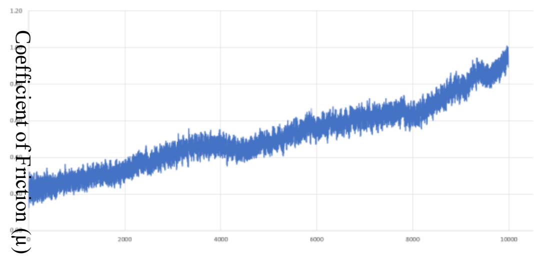
In Figure 24 and Figure 25, the results of two tests outputted from the manufactured tribometer can be seen. The purpose of these two tests is to compare the effect of longer test times and different speeds using the manufactured tribometer. The sample is a D2 steel substrate in both tests. The first test is run with a radius of 10 mm, a speed of 100 mm/s, a load of 1 N and 15 minutes of run time. The y axis shows the coefficient of friction value calculated by the manufactured tribometer. The x axis shows the amount of data points that are recorded. A total of 10000 data points are recorded in both experiments during the 15 minutes of testing time. Each point of data is approximately recorded every 0.09 seconds. In the graphs, 10000th data point equals to the 900th second mark.

In Figure 25, the result of the last test conducted on the manufactured tribometer can be seen. This test is run on the same sample as the previous one. The main differences between the two tests were that this one is run on a 12 mm radius and 50 mm/s speed. Results show us that the friction coefficient does not exceed 1.01 and the mean is also lower than the faster test. The lower mean coefficient of friction results may be due to multiple factors. As the speed is lower than the previous tests, heat generated during the sliding process would be less. Excessive heat generated with higher speeds can lead to increased coefficient of friction results. Another reason could be that higher speeds could lead to more wear and abrasion between two surfaces. At lower speeds, lower wear and abrasion levels would cause less friction between two surfaces. In both experiments, the maximum coefficient of friction results observed were slightly above 1. The mean coefficient of friction value shown in the curve is under 1. However, the oscillations of force measurements show a variance. As can be seen in the literature, friction coefficients can even be higher than 1, depending on the surface conditions. It is important to note that finding the optimal testing parameters is crucial for conducting tribological experiments.



Min: 0.29	Max: 1.10	Mean: 0.84

Figure 24. Coefficient of friction versus time via the manufactured device with longer test time and higher speed



Min: 0.12	Max: 1.01	Mean: 0.51

Figure 25. Coefficient of friction versus time via the manufactured device with longer test time and lower speed

9. CONCLUSION

In this work, a pin-on-disk tribometer is designed and manufactured. The developed tribometer offers competitive specifications to the mass produced and professional tribometers. In the design process, the parts are made as light as possible, and the dimension and materials are changed according to material availability. Also, the electrical components are chosen according to the budget and requirements. To save on manufacturing cost, every part is made in the ATILIM University Manufacturing Laboratories using CNC machining. The total budget allocated for designing, manufacturing, and testing the manufactured tribometer is 10,000 Turkish Lira for a single unit. Comparatively, the CSM pin-on-disk tribometer costs 70,500 Swiss Franc, making it 22976% more expensive. Likewise, there are also significant differences in terms of weight between the two tribometers. The CSM tribometer weighs 50kg, making it hard to carry around if needed. The manufactured tribometer weighs just 10kg which is an 80% difference, making it portable enough to carry around when needed. Design and power calculations are done and the properties of the parts that are manufactured are determined according to these calculations. The tribometer is designed to adhere to the ASTM G99 and G115 standards. In the testing phase, the tribometer is compared to a CSM branded professional tribometer using similar tests. During the tests, the same parameters and the same samples are used to ensure the integrity of the comparisons. The manufactured tribometer has the capability of gathering real-time data as the tests run. Arduino boards allow the tribometer to stream real time data directly to the computer software. This makes it possible to draw a time graph of the coefficient of friction data and make comparisons. Data streaming also allows researchers to filter, manipulate or perform various data analysis tasks after the test is finished. When the results are observed, the curves for the coefficient of friction and the mean values between the professional tribometer and the tribometer made in this project are found very similar. Some other tests are run to confirm that the tribometer is outputting reasonable data with different parameters. After confirming all the results from the tests, the project was deemed a success. The manufactured tribometer could potentially be enhanced by integrating sensors to record temperature data during tests. Finally, the tribometer could be modified to enable testing with different kinds of lubricants. Current design is open to further development as needed.

DİSK ÜSTÜNDE PİM TRİBOMETRE TASARIMI VE İMALATI

Bu makalenin ele almış olduğu projenin konusu, bir disk üstünde pim tribometre tasarımı ve imalatıdır. Tasarlanmış tribometrenin karşılaması gereken gereksinimler; 0-1400 mm/s arası hızda, 0-10 N arası normal yükte ve 6 mm 100 Cr6 çelik veya alümina (Al_2O_3) top ile deney yapılabilmesidir. Tribometrenin gerekli parçaları ATILIM Üniversitesi İmalat Laboratuvarı'nda CNC tezgâh kullanılarak gerçekleştirilmiştir. Tribometre tasarlanırken, taşınabilirlik, hafiflik, düşük maliyet ve deney sırasında gerçek zamanlı bir şekilde veri akışı sağlanabilmesi en önemli öncelikler olarak belirlenmiştir. Aynı zamanda tasarım ve üretim süreçlerinde ASTM G99 ve G115 standartları göz önünde tutulmuştur. Düzenek kurulurken, sürtünme katsayısını hesaplamak amacıyla veri toplama işlemi için bir yük hücresi kullanılmıştır. Hız gereksinimini karşılayacak bir adım motoru seçilmiştir. "Arduino" aracılığı ile kontrol edilebilecek şekilde kod yazılıp, veri toplamak ve sürtünme katsayısının grafiğini gerçek zamanlı olarak elde etmek için Microsoft Excel'in "Data Streamer" eklentisi kullanılmıştır. Bu şekilde hem deney sırasında hem de deneyin tamamlanması ardından veri işleme görevleri yapılabilmektedir. Sunulan cihaz, CSM tarafından üretilmiş, profesyonel bir disk üstünde pim tribometre ile deneysel ortamda karşılaştırılmıştır. Karşılaştırmalarda aynı parametreler ve aynı şekilde hazırlanmış numuneler kullanılmıştır. Numune hazırlama süreçleri detaylı bir biçimde belirtilmiştir. Testler sırasında 100Cr6 çelik top kullanılmış olup, cihazın alümina (Al_2O_3) topları ile de deney yapabilme kabiliyeti vardır. Alümina (Al_2O_3) topların kullanım alanları ve çelik toplardan farkları, nedenleri ile belirtilmiştir. Karşılaştırmalar sonucunda, sunulan tribometre ile CSM tribometreden alınan sürtünme katsayısı verileri karşılaştırılabilir bir oranda çıkmıştır. Proje, tanımlanan gereksinimleri karşılamış ve başarılı bir şekilde sonlandırılmıştır.

Anahtar Kelimeler: Tribometre Tasarımı, İmalat, Tribolojik Test, Sürtünme Katsayısı Ölçümü, Yüzey Karakterizasyonu

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