



25<sup>th</sup> ABCM International Congress of Mechanical Engineering  
October 20-25, 2019, Uberlândia, MG, Brazil

**COB-2019-1689**

## **DESIGN AND CONSTRUCTION OF A PIN-ON-DISK EXPERIMENTAL BENCH TO DETERMINE THE FRICTION COEFFICIENTS OF MATERIALS**

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**Abstract.** *The present work deals with the design and fabrication of a pin/ball on disk type tribometer, seeks to determine using experimental tests and analysis of material properties, the coefficients of friction as well as the wear volume of certain pairs of engineering materials. The project aims to meet the need of users, researchers or technicians, whether for studies of science and research or for industrial purposes of development or quality control. The tribometer was effective and the experiments performed showed satisfactory results.*

**Keywords:** *ASTM G 99, pin-on-disk, tribology, wear.*

### **1. INTRODUCTION**

Every mechanical system is subject to deterioration processes. This deterioration leads to the appearance of flaws that may disturb the continuity and quality of the service (production) (Lago, 2007). Unexpected breakdown of a machine or equipment results in an abrupt stop, usually leading to heavy losses and loss of production time (Cunha, 2005).

Tribology is the science that studies the friction between bodies in motion, wear as a natural effect of this phenomenon and lubrication to avoid this wear (Ludema, 1996). Tribological trials are very important and they are increasingly indispensable in the industry (Bhushan, 2013; Ying, S., Yupeng, Y., 2017). This science can help define the planning of mechanical maintenance routines, as well as analyze tribological properties of new engineering materials, such as polymers and ceramics (Silva et al., 2006; Larson, M. G., Timpe, S. J., 2017).

Tribology experiments are performed in a tribometer. One commonly used to accurately assess the wear behavior by sliding pairs of materials is the pin/ball-on-disk (Bayer, 2004). This equipment has been referred to as one of the best at representing the study of friction and wear of materials, and which presents better reproducibility of results in laboratory procedures (Ramos et al., 2014).

The pin/ball-on-disk tribometer has contributed to several tribological types of research lately. Recent work (Souza et al., 2019) investigated the feasibility of using *Jatropha* and *Tung*-based vegetable oils as bio-lubricants for the use in the formulation and development of environmentally correct machining fluids. Pauly et al. (2019) observed the structural behavior of the Incoloy 800HT and Inconel 617 alloys for application in the high-temperature gas reactor concept.

Recently, Hamilton and Muñoz-Escalona (2019) studied the improvement of wear of two polymer composites with the incorporation of carbon fibers and glass fibers in the polymer matrix. Qiu et al. (2019) investigated the wear of the Ti-45AL-7Nb-0.3W alloy pin with zirconia disk at ambient temperature in different environments such as argon, hydrogen and a mixture of nitrogen, air, and oxygen. Haghghat-Shishavan et al. (2019) observed the wear of an alumina coating on AA7075 aluminum alloy against a SAE 52100 steel disk.

Thus, having as a motivation the scientific contributions of this model of equipment to the researchers, the purpose of this study is to design and construct a tribometer of pin/ball-on-disk type, to perform tests for measuring the coefficient of friction, as well as to calculate the volume of material lost, of certain pairs of materials.

## 2. BACKGROUND

Wear tests of different materials through a pin-on-disk are conducted by the American Society for Testing and Materials (ASTM) standard G99: Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. The controlled test parameters are: load [N], speed [m/s], distance [m], temperature [°C] at the pin and/or disk, and atmosphere (laboratory temperature, relative humidity, lubricant, and so on).

The premises to meet the requirements of the design are: the pin must be pressed against the disk by a specific load (normal force), usually by means of a lever with fixed masses attached to it; wear results are usually obtained by performing tests for a given sliding distance, as well as load and speed values, ranging from 0.3 to 3 [rad/s] (60 to 600 rpm) (ASTM, 2017).

In addition, according to the standard, the machine must be equipped with a revolution counter, which will record the number of revolutions of the disk and, preferably, is able to turn the machine off after a certain pre-selected number of revolutions. The system must also be able to measure the friction force (for example, through a load cell) to determine the coefficient of friction. Thus, using this method, it is possible to determine and study friction and wear behavior in materials, with varying time and distance, contact pressure, speed, temperature, humidity, and lubrication.

## 3. MATERIAL AND METHODS

Based on the standard aforementioned, an instrumented tribometer was designed, constructed and validated.

### 3.1 Design and construction of the equipment

Figure 1.a illustrates the CAD environment project, Figure 1.b, an illustration of the front of view of the machine during operation, Figure 1.c, an illustration of its side view.

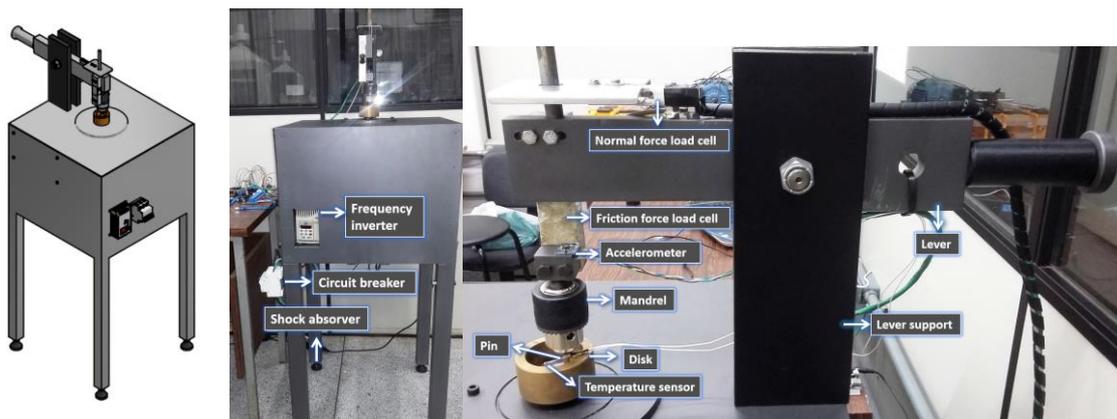


Figure 1. Pin/ball-on-disk: a) virtual prototype of the equipment, b) its front view, and c) its side view.

### 3.2 Automation and Instrumentation

Figure 2.a illustrates the electronic components used in the machine, whereas Fig. 2.b depicts the power transmission system.

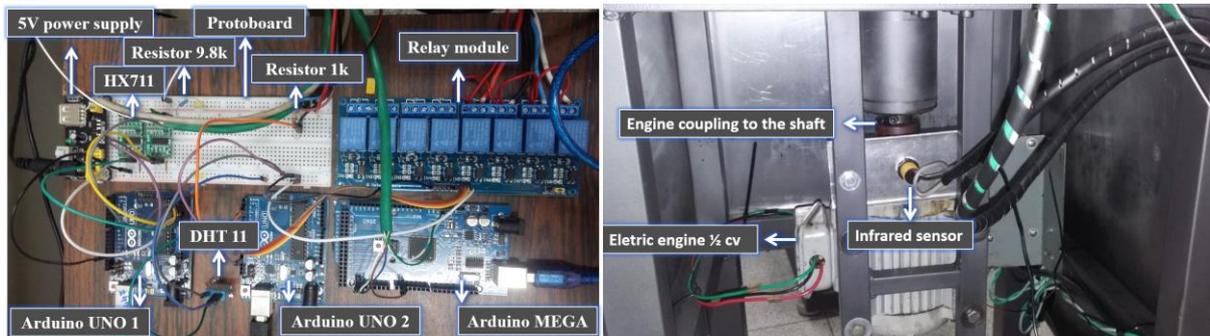


Figure 2. Electrical and electronic components used in the tribometer: a) electronic components and b) power transmission system.

The components used for the control of the machine were an Arduino microcontroller UNO, a frequency inverter (Brand: WEG, Model: CFW 08), an E18 - D80NK infrared proximity sensor and an 8-channel relay module of 5 volts, from which only 4 channels were used for this application. To meet the requirements of the ASTM G-99 standard for the test control, initially the infrared proximity sensor was used to count the pulse of each revolution through the coupling screw from the motor to the shaft, in which the drive frequency is determined for each desired rotation.

Seven different frequencies were set corresponding to each rotation in the CFW 08 inverter, ranging from 60 to 600 [rpm] with a progressive interval of 90 [rpm] between the rotations, which are driven by the 8-channel relay module of 5 volts through binary combinations programmed in Arduino.

To begin the test, the user must give as input the radius of the pin with respect to the center of the disk [mm], the sliding distance [m] and the desired rotation [rpm]. Then, the algorithm calculates the number of cycles between the circumference and the sliding distance, and the serial monitor prints the number of each cycle, the velocity [m/s] and the rotation [rpm] that are obtained through the infrared proximity sensor. Figure 3 shows a schematic illustration of the control system.

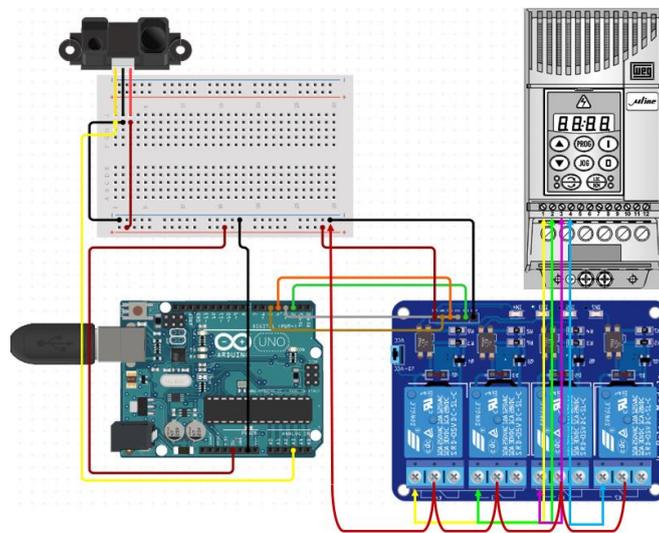


Figure 3. Electrical and electronic components and connections for the control system.

For the acquisition system of the friction and normal forces, an Arduino microcontroller UNO, two load cells and two HX711 converter modules were used. The DHT11 sensor was used to monitor humidity and ambient temperature, and an NTC 3950 thermocouple sensor was used to measure the contact surface temperature between the pin and the disk.

Figure 4 shows the schematic representation of the electrical and electronic components and the connections performed by the acquisition system of the friction and normal forces, pin-to-disk temperature, humidity, and ambient temperature.

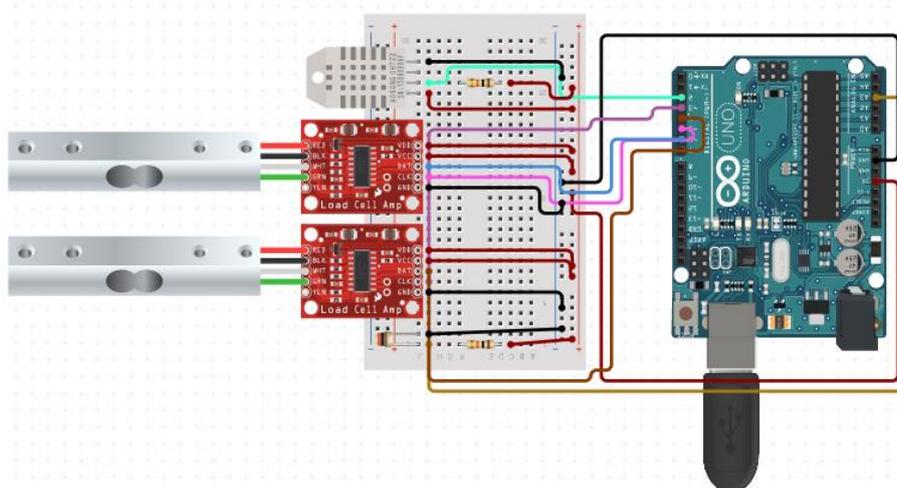


Figure 4. Electrical and electronic components and connections for the acquisition of signals.

Additionally, an accelerometer, triaxial gyroscope MPU 6050 and an Arduino MEGA microcontroller were used to measure the vibration signals. Figure 5 represents the schematic diagram for the acquisition of these signals.

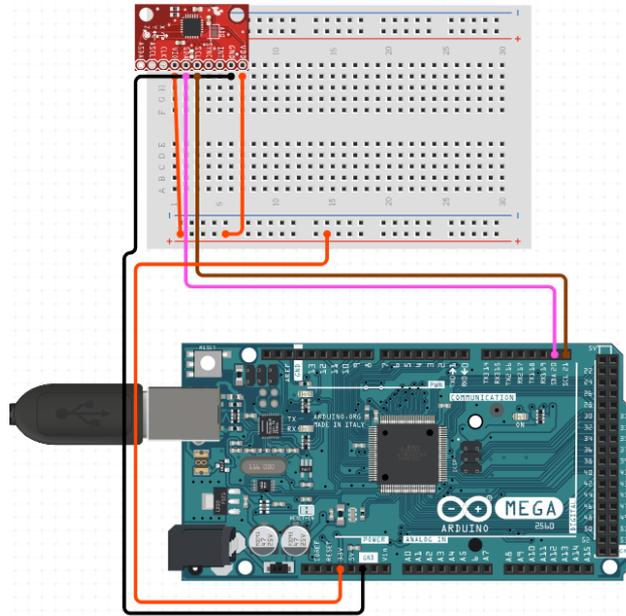


Figure 5. Electrical and electronic components and connections for measuring vibration signals.

### 3.3 Mathematical equations

Equation (1) was used to measure the wear of the samples. Firstly, it is necessary to know the density [ $g / m^3$ ] and the mass loss [ $g$ ] of the material after the test. Wear is given in volume loss [ $m^3$ ] and must be calculated for the pin and the disk separately.

$$v\alpha [m^3] = \frac{MI [g]}{p [g / m^3]} \quad (1)$$

Where  $v\alpha$  is the volume loss, MI is the mass loss and p is the density of the material.

The coefficient of friction [ $\mu$ ] can be determined by the ratio between the friction force [N] to the normal load [N] as presented by Eq. (2).

$$Fat = \mu \cdot N \quad (2)$$

Where  $\mu$  is the coefficient of friction, Fat is the friction force and N is the normal force.

Assuming hemispherical wear particles of the same radius as the contact areas, the mechanism of adhesive wear for plastic contact gives the following expression for the wear rate (Archard, 1953).

$$v\alpha [m^3] = \frac{1}{3} \frac{Wx}{H} = \frac{kWx}{H} \quad (3)$$

Where W is the applied load [N], H is the hardness [ $N/m^2$ ] of the sliding materials,  $v\alpha$  is the volume of wear [ $m^3$ ], x is the sliding distance [m], and k is a constant related to the wear coefficient.

Ludema and Ajayi (2019) also describe the wear rate according to Eq. (4).

$$\psi [m^3 / s] = k \left( \frac{WV}{H} \right) \quad (4)$$

Where  $W$  is the applied load [N],  $H$  is the hardness [N/m<sup>2</sup>] of the sliding materials,  $V$  is the sliding speed [m/s],  $k$  is a constant related to the wear coefficient, and  $\psi$  is the wear rate [m<sup>3</sup>/s].

The root-mean-square level (RMS) used for processing the signals obtained in this work is given according to equation 5;

$$F(RMS),i = \sqrt{\frac{1}{NL} \sum_{j=1}^{NL} |F_j|^2}, i=1, \dots, L \quad (5)$$

Where  $L$  is the number of windows used,  $NL$  is the number of points in each window, which is always lesser than  $N$  ( $NL < N$ ), the total number of points in the signal.

The experiments were conducted with the following conditions: dry sliding, applied normal force of 10 [N], a speed of 0.1 [m/s], an ambient temperature of 22 [°C] and relative humidity varying from 32 to 35%. The sliding distance was defined to be equal to 1000 [m], and the nominal diameter of the disk wear track was 16 [mm].

Two experiments were carried out: in the first case, SAE 1020 steel was used for both pin and disk, whose density is 7.87 [g/cm<sup>3</sup>]. For the second case, the SAE 1020 steel was used for the pin and a copper disk, whose density is 8.93 [g/cm<sup>3</sup>].

#### 4. RESULTS AND DISCUSSION

For the first experiment, initially, both pin and disk were weighed on an analytical balance with a resolution of 0.0001 [g] (Brand: Shimadzu, Model: AUX 320) and presented a mass of 8.55 and 206.75 [g], respectively. After completing the wear test, both pin and disk were weighed again and presented a mass loss of 0.0843 [g] and 0.0684 [g].

For the second experiment, again, the samples were weighed initially with a mass of 8.41 [g] for the pin and 561.15 [g] for the disk. After completing the wear test, the samples were weighed again and presented a mass loss of 0.0673 [g] for the pin and 0.0248 [g] for the disk.

In repeat-pass sliding with the pin-on-disk specimen shape, the wear loss from the pin is greatest for metal combinations unless the disk is much softer than the pin (Ludema and Ajayi, 2019).

With these data, the volume losses were calculated using Eq. (1). For the first experiment, the volume losses calculated were equal to  $1.071 \times 10^{-8}$  [m<sup>3</sup>] for the pin and  $8.691 \times 10^{-9}$  [m<sup>3</sup>] the disk. For the second experiment, the volume losses calculated were equal to  $8.551 \times 10^{-9}$  [m<sup>3</sup>] for the pin and  $2.777 \times 10^{-9}$  [m<sup>3</sup>] for the disk.

According to Totten and Bruce (2006), the proportionality constant  $k$  is denoted as wear coefficient and can be obtained using Eq. (3). For the first case, the constant  $k$  presented a value of  $1.418 \times 10^{-3}$  for the pin and  $1.151 \times 10^{-3}$  for the disk. In the second case,  $k$  presented a value of  $1.132 \times 10^{-3}$  for the pin and  $2.179 \times 10^{-4}$  for the disk. The value of  $k$  ranges typically from  $10^{-8}$  to  $10^{-4}$  for mild wear, and from  $10^{-4}$  to  $10^{-2}$  for severe wear for most material combinations, depending on the operating conditions (Bhushan, 2013).

Using Eq. (4), the wear rate can be obtained. It is generally considered as the amount of wear removed from the softer surface of the two surfaces (Bhushan, 2013). For the first case, where the pair of materials are equal, the mean between the wear coefficients  $k$  was used, and for the second case, the softer material was used, in this case, copper. Thus, a wear rate of  $9.705 \times 10^{-13}$  [m<sup>3</sup>/s] was obtained for the first experiment, and  $2.778 \times 10^{-13}$  [m<sup>3</sup>/s] for the second.

A change in surface conditions such as a breakdown of a protective film changes the coefficient of friction at the most by a factor of 2 or 3, whereas the wear rate may change by one or two orders of magnitude (Archard and Hirst, 1956). Following is a short compilation of specific wear data obtained using a pin and disk system with a load of 0.4 kgf and a speed of 1.8 m/s adapted from Archard and Hirst (1956).

Table 1. Wear rate for certain pairs of materials.

| Wearing Surface | Counter Surface | W (mm <sup>3</sup> /m) | HB (kg/mm <sup>2</sup> ) | $\mu$ | K                    |
|-----------------|-----------------|------------------------|--------------------------|-------|----------------------|
| Mild Steel      | Mild Steel      | $1.57 \times 10^{-2}$  | 186                      | 0.62  | $7 \times 10^{-3}$   |
| 60-40 Brass     | Tool Steel      | $2.40 \times 10^{-3}$  | 95                       | 0.24  | $6 \times 10^{-4}$   |
| PTFE            | Tool Steel      | $2.00 \times 10^{-4}$  | 5                        | 0.18  | $2.4 \times 10^{-5}$ |
| Stellite        | Tool Steel      | $32 \times 10^{-6}$    | 690                      | 0.60  | $5.5 \times 10^{-5}$ |
| Ferritic SS     | Tool Steel      | $27 \times 10^{-6}$    | 250                      | 0.53  | $1.7 \times 10^{-5}$ |

Available from: Archard and Hirst (1956).

Through Tab. 1 and using Eq. (4), the wear rate for the mild steel against mild steel presented a value of  $2.763 \times 10^{-11}$ . Therefore, comparing Table 1 to our results, wear rates of material combinations range more widely than their coefficients of friction and thus it is to be expected that deviations from regular behavior will be more noticeable for wear (Archard and Hirst, 1956).

Through the data acquisition system and using the OCTAVE software for signal processing, the graphs of distance vs friction forces were obtained, as shown in Fig. 6. Figure 7, in turn, presents the same plot, but now considering the root-mean-square (RMS) level of the original signal. To do so, the total number of points  $N$  was divided into shorter windows, such that each point in Fig. 7 represents one of these windows, as expressed by Eq. (5).

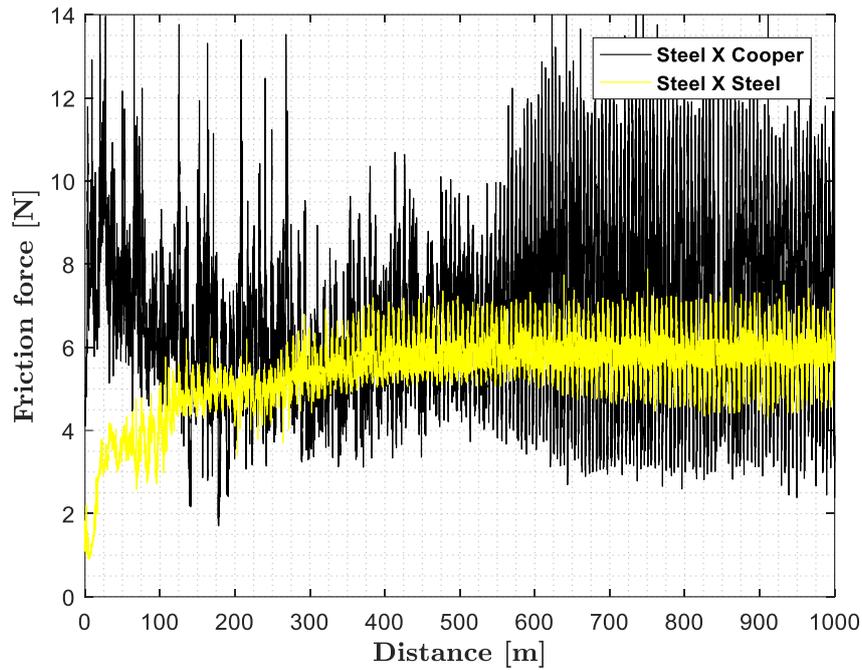


Figure 6. Friction forces determined in the tests.

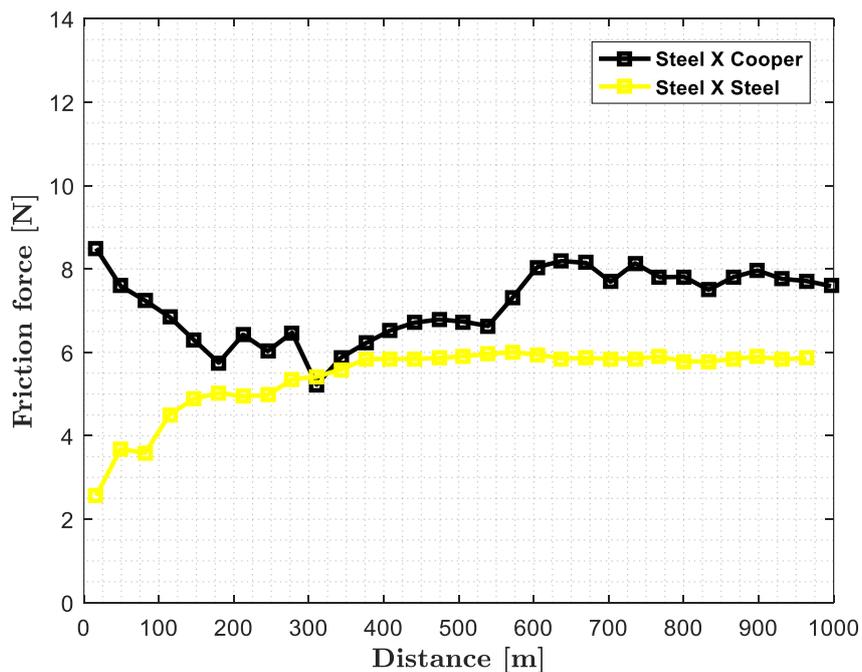


Figure 7. Root-mean-square level of the friction forces.

Using Eq. (2), the coefficients of friction were determined and they are presented in Fig. 8. for the first experiment, and in Fig. 9. for the second experiment.

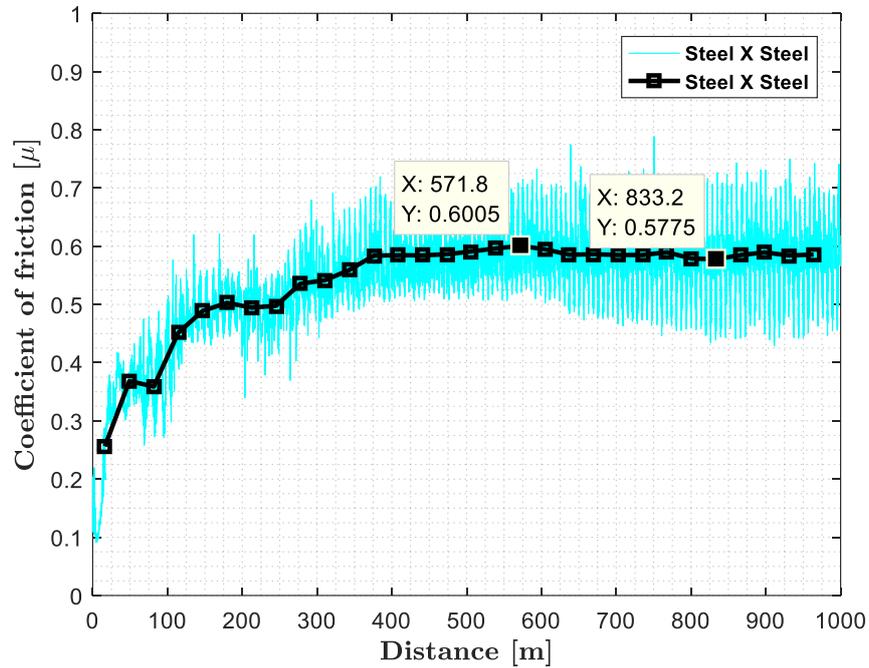


Figure 8. Steel coefficient friction, and the root-mean-square level indicated by the black line.

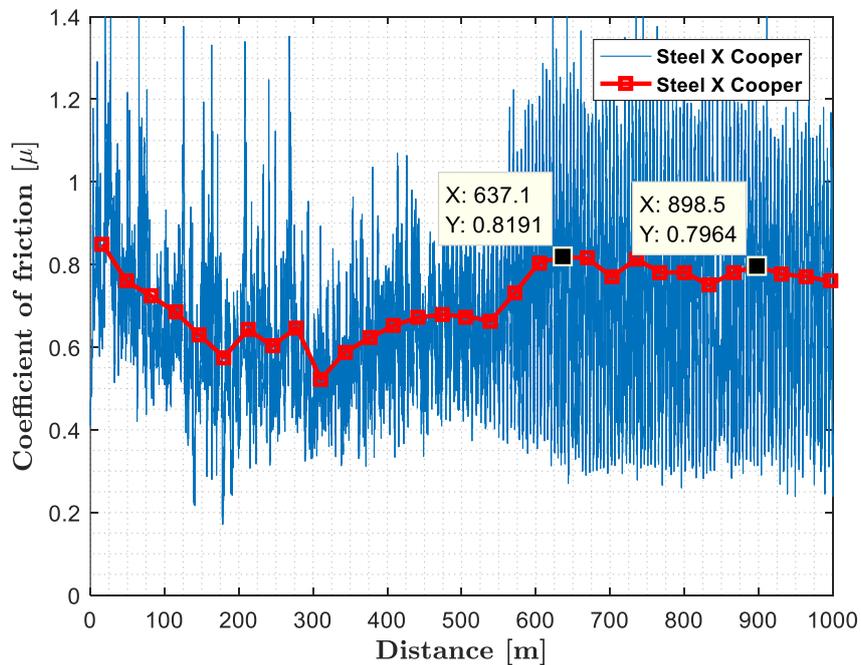


Figure 9. Coefficient of friction between steel and copper, and the root-mean-square level indicated by the red line.

Figure 8 shows that the coefficient of friction calculated for the first case varies around 0.57 and 0.60, close to the coefficient of friction between steel and steel found in the literature, which is 0.57. Analyzing Fig. 9, the coefficient of friction varies around 0.79 and 0.81, close to that found in the literature that is 0.8. The coefficients of friction found in the literature are presented in Tab. 2.

Table 2. Coefficients of friction for certain pairs of materials.

| Material 1 | Material 2 | Coefficients of friction |         |        |           |
|------------|------------|--------------------------|---------|--------|-----------|
|            |            | Dry                      |         | Greasy |           |
|            |            | Static                   | Sliding | Static | Sliding   |
| Steel      | Steel      | 0.74                     | 0.57    | -      | 0.09-0.19 |
| Steel      | Copper     | -                        | 0.8     | -      | -         |

Available from: [http://www-eng.lbl.gov/~ajdemell/coefficients\\_of\\_friction.html](http://www-eng.lbl.gov/~ajdemell/coefficients_of_friction.html).

Figure 10 shows the temperature variation by the sliding distance for each test.

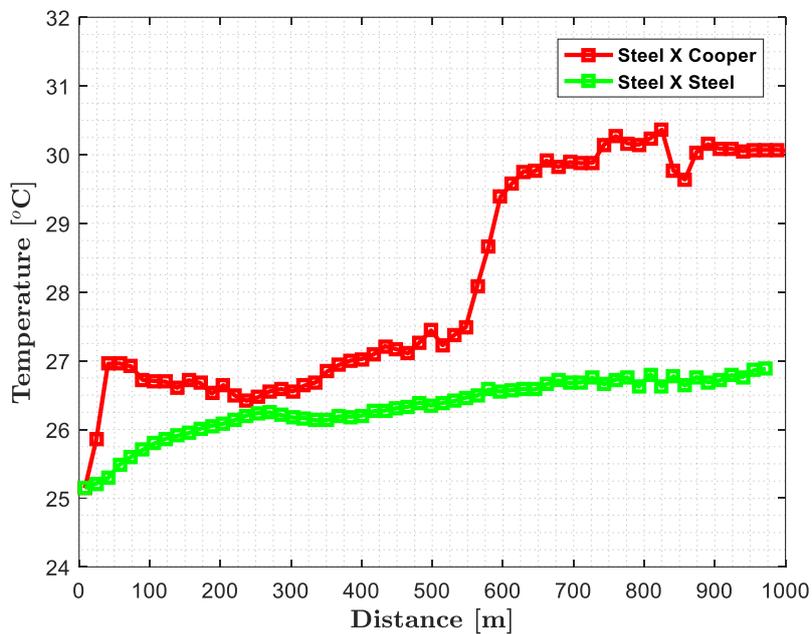


Figure 10. Graph of the temperature variation by the sliding distance.

One can observe in Fig. 10 that for the test with both steel pin and disk a temperature variation of 1.64 [°C] was obtained. For the test with steel pin and copper disk, a temperature variation of 5.09 [° C] was obtained. The great difference of temperature variation represented in these tests is justified by the fact that copper has a higher thermal conductivity than steel, as presented in Tab. 3.

Table 3. Thermal conductivity of metals.

| Material | Thermal conductivity [W/mk] |
|----------|-----------------------------|
| Steel    | 52                          |
| Copper   | 372                         |

Available from: <http://www.protolab.com.br/Tabela-Condutividade-Material-Construcao.htm>.

## 5. CONCLUSION

The design and fabrication of the pin/ball-on-disk tribometer presented interesting results for its structural and instrumentation system. After analyzing two different combinations for the pin and disk test pair, it was possible to determine two different coefficients of friction and variation of the temperature.

The term  $k$  is usually interpreted as the probability that transfer of a material fragment occurs or a wear particle is formed considering the friction resulting from the sliding between two surfaces. In both cases, severe wear was expected, as the tests were in unlubricated conditions, the experimental tests showed an expected wear range being the first case  $1.418 \times 10^{-3}$  for the pin and  $1.151 \times 10^{-3}$  for the disk. In the second case the values obtained were  $1.132 \times 10^{-3}$  for the pin and  $2.179 \times 10^{-4}$  for the disk within range mentioned by Bhushan (2013).

Archard and Hirst (1956) state that, the wear coefficient and wear rate depend on the normal load, except for low sliding speeds. Furthermore, there will be a significant increase in the temperature of the surface and the temperature of the friction surfaces will depend on the load. This effect of temperature is probably one of the most important reasons why proportionality between wear rate and load is not generally observed.

Therefore minor changes in surface conditions that produce no detectable change in friction may lead to a marked change in the wear rate, which justifies the variation in the wear rate of the first case  $9.705 \times 10^{-13}$  [m<sup>3</sup>/s] compared to (Archard) data for mild steel against mild steel  $2.763 \times 10^{-11}$  [m<sup>3</sup>/s] and for the second case mild steel against cooper  $2.778 \times 10^{-13}$  [m<sup>3</sup>/s]. Comparing the values obtained with those present in the literature, we can see that the results obtained were satisfactory.

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