Determination of the coefficient of dynamic friction between coatings of alumina and metallic materials

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Abstract: This project aims to determine the coefficient of dynamic friction between micrometric size coatings of alumina and metallic materials (Steel and aluminium); the methodology used to achieve the proposed objective consisted of 4 phases, in the first one was developed a procedure that allowed, from a Pin on Disk machine built based on the specifications given by the ASTM G99-05 standard (Standard test method for wear tests with a Pin on Disk machine), to determine the coefficient of dynamic friction between two materials in contact; subsequently the methodology was verified through tests between steel-steel and steel-aluminium, due to these values are widely reported in the literature; as a third step, deposits of alumina particles of micrometric size were made on a steel substrate through thermal spraying by flame; finally, the tests were carried out between pins of steel of aluminium and alumina coating to determine the coefficients of dynamic friction between these two surfaces. The results of the project allowed to verify that the developed methodology is valid to obtain coefficients of dynamic friction between surfaces in contact since the percentages of error were of 3.5% and 2.1% for steel-steel and aluminium-steel, respectively; additionally, it was found that the coefficient of friction between steel-alumina coatings is 0.36 and aluminium-alumina coating is 0.25.

1. Introduction
Friction is defined as the resistance to relative displacement between two surfaces that are in contact and depends on the characteristics of the surfaces that are interacting with each other and this phenomenon is quantified through the friction force which prevents or delays the displacement of one body with respect to another or on the surface with which it is in contact. Friction exists even when there is no relative movement between the two bodies and this is known as static friction; on the contrary if it is present the relative movement, it is designated by the name of dynamic friction.

The friction force has a magnitude equal to the product between the coefficient of friction and the resulting normal force due to the proper weight of the elements and the external forces acting on the system. The coefficient of friction is a dimensionless parameter and is characteristic of each pair of materials that are in contact and it also depends on many other factors such as temperature, roughness, relative speed between surfaces, etc. [1,2].

In mechanical systems where the elements interact with each other through sliding contacts, friction plays a very important role [3,4]; The determination of the friction force is generally modelled by Coulomb’s La, established experimentally in 1781, and defines that the frictional force that can exist in the bodies in contact is directly proportional to the value of the normal force of contact between them; the constant of proportionality is the coefficient of friction. Many experimental studies determine the
coefficient of dynamic friction through the consideration of only a translation movement between the surfaces in contact [5-7], tests that allowed to estimate the normal and frictional forces present between materials; the dependence of the friction force of the displacement and velocity; and the modelling of the friction interface under conditions of nonlinear dynamic analysis. Other researchers have used rotational systems to experimentally determine the coefficient of friction, among which stand out the pin on disk system [8,9], circular spin plates [10] and roller systems and radially loaded discs [11]. It is also used the measurement of the angular displacement and the torque used in the test for the determination of the variables involved in the friction phenomenon, for different applications [12,13].

The pin on disk equipment are designed to perform adhesive wear tests, their specifications and the procedure for the execution of the tests are listed in the ASTM G99-05 (Standard test method for wear tests with a Pin on Disk machine) which is a standard method for obtaining valid data. For wear testing through this equipment are required two specimens, the first is a pin which is positioned perpendicular to the other specimen which is usually a circular disk. The machine causes a relative displacement between these specimens which result in the formation of a wear path on the disk; the pin-shaped specimen is pressed onto the disk with a specific load and that specimen is fastened to a positioning device with counterweights. Wear reports are made in terms of loss of volume.

Despite the simplicity of the measurement and calculation, there are practical challenges to accurately quantify these basic tribological parameters. Friction is an atypical process of non-equilibrium and slippage often leads to wear which is highly stochastic. The values of the coefficient of friction and wear rates reported in the literature typically show a wide variation even for nominally identical tests; the origin for these variations is often unknown [14-16].

This paper reports the results obtained of the dynamic coefficient of friction for alumina coatings deposited through thermal spray by flame process from particles of micrometric size and two different metals (steel and aluminium) obtained from tests in a pin on disk equipment.

2. Methodology

2.1. Development of a procedure that determines the coefficient of dynamic friction
The pin-on-disk equipment are used to quantify the loss of material originated during wear tests; however, the determination of the coefficient of friction must be performed indirectly through the measurement of some parameters during the test to find the friction force originated and from this value and based on Coulomb’s law determine the searched parameter.

2.2. Validation of the procedure for the determination of the coefficient of dynamic friction
The verification of the procedure developed for the calculation of the coefficient of dynamic friction was carried out through the realization of tests for two different configurations (steel-steel and steel-aluminium), since they are data quite reported in the literature. Tests were performed with an applied load of 10N, the time of each test was 5 minutes and the data were taken at constant time intervals of 10 seconds. A total of 10 tests were done for each pair of materials tested.

2.3. Deposit and characterization of alumina coatings
The alumina coatings were made through the thermal spraying by flame process, using an Eutalloy 85 BX gun, which is adapted to a conventional oxyacetylene combustion equipment. The distance between the torch and the base material was approximately 30cm, with an inclination to the horizontal of 60°. The oxygen pressure used was 25psi and that of the acetylene was 5psi.

2.4. Realization of tests on alumina-coated specimens
The coated specimens were tested in the pin-on-disc equipment using steel and alumina pins to determine the coefficient of dynamic friction between the coating and these two metals. The procedure and test parameters used for these tests was the same as that followed for the validation of the methodology.
3. Obtained results

3.1. Procedure for the determination of the coefficient of dynamic friction

The procedure developed is based on the determination of the electrical power consumed in the test (equation (1)), which is calculated as the subtraction between the value obtained during the test and the power consumed under vacuum conditions (without specimen). For the determination of the electrical power, the current (I) and the voltage (V) being supplied to the motor through the network were measured.

\[ P_e = (\sqrt{3} \times I \times V \times \cos \phi)_\text{test} - (\sqrt{3} \times I \times V \times \cos \phi)_\text{vacuum} \]  

(1)

The cosine of the angle \( \phi \), is the power factor of the motor used to carry out the tests.

The mechanical power is obtained by multiplying the electric power consumed by the motor efficiency (\( \eta \)) and this magnitude is the product of the torque (\( T \)) used in the test by the angular velocity that the specimen must have (\( \omega \)), 300rpm defined by the standard. From the above, it is defined that the torque consumed in the test can be obtained from equation 2.

\[ T = \frac{P_e \eta}{\omega} \]  

(2)

The multiplication of the friction force (\( F_f \)) by the distance of the pin to the centre of rotation (\( r \)) of the specimen determines the torque that is applied for the test (\( T \)); in addition, Coulomb's law states that there is a proportionality between the normal (\( N \)) and the friction force by the coefficient of friction (\( \mu \)) present between the two materials. From the above it is deduced that through equation 3 the coefficient of dynamic friction can be quantified between the material of the coating and the one of manufacture of the pin.

\[ \mu_K = \frac{T}{N \times r} = \frac{P_e \eta}{N \times r \times \omega} \left[ (\sqrt{3} \times I \times V \times \cos \phi)_\text{test} - (\sqrt{3} \times I \times V \times \cos \phi)_\text{vacuum} \right] \times \frac{\eta}{N \times r \times \omega} \]  

(3)

The value of the normal is obtained from the static equilibrium conditions of the system where is installed the pin, which is shown on Figure 1.

![Free body diagram of the system where the pin is installed.](image-url)
By means of a summation of moments at the point where $R_y$ is found, there is obtained the equation 4 that allows to calculate the normal that appears in the specimen in a disc shape.

$$N = 16.01 + W_{pin} \ [N]$$ (4)

Replacing the value of normal in equation 3 gives the equation 5 which allows to calculate the coefficient of dynamic friction between two materials.

$$\mu_K = \left[\frac{(\sqrt{3} I V \cos \phi)^{test} - (\sqrt{3} I V \cos \phi)^{vacuum}}{16.01 + W_{pin}}\right] \eta (5)$$

3.2. Validation of the procedure for the determination of the coefficient of dynamic friction
Using the equation 5, the coefficient of dynamic friction between steel - steel and steel - aluminium was determined; the requested values from the equation are defined by the characteristics of the motor arranged in the equipment ($\cos \phi=0.65$ y $\eta=0.602$), the test conditions defined by the standard ($r=0.02\ m$ y $\omega=10\pi rad/s$) and the measurements of current, voltage and weight of the pin. The results obtained from the tests are listed on Figure 2.

![Figure 2. Coefficient of dynamic friction between steel-steel and steel-aluminium obtained through the developed methodology.](image)

The obtained coefficient of dynamic friction between steel-steel was 0.553, while for steel-aluminium was 0.459; which represents a 3.6% and a 2.2% of error respectively regarding the values reported on the literature. Additionally, the classical behaviour of this variable is observed when a static coefficient of friction greater than the dynamic coefficient is obtained from the tests.

3.3. Realization of test on alumina-coated specimens
The results of the coefficient of dynamic friction obtained from the tests performed on alumina-coated specimens from particles of micrometric size and deposited through a thermal spray by flame process and using steel and aluminium pins are listed in Figure 3. The coefficients of dynamic friction between Steel-alumina coating and aluminium-alumina coating was 0.35 and 0.25 respectively.
Figure 3. Coefficient of dynamic friction between steel-alumina and aluminium-alumina.

4. Conclusions
The developed methodology allows to determine the coefficients of dynamic friction between two materials using a pin on disk wear equipment.

The percentages of error in the magnitudes of the coefficients of dynamic friction between steel-steel and Steel-aluminium was 3.6% and 2.2% respectively.

The coefficients of dynamic friction between Steel-alumina coating and aluminium-alumina coating was 0.35 and 0.25 respectively.

References
[1] Maegawa S, Itoigawa F and Nakamura T 2015 Effect of normal load on friction coefficient for sliding contact between rough rubber surface and rigid smooth plane Tribology International 92(1) 335-343
[2] Popov V L 2010 Contact mechanics and friction: physical principals and applications (Heidelberg: Springer)
[3] Dweib A H and D’Souza A F 1990 Self-excited vibrations induced by dry friction, part 1: Experimental study J. Sound Vib. 137(2) 163-175
[4] Kang J and Krousgrill C M 2010 The onset of friction – induced vibration and spragging J. Sound Vib. 329(17) 3537-3549
[5] Hoskins E R, Jaeger J C and Rosengren K J 1968 A medium-scale direct friction experiment Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 5(2) 143-152
[6] Worden K, Wong C X, Parlitz U, Hornstein D, Tjahjowidodo T, Al-Bender F, Rizos D D and Fassois S 2007 Identification of pre-sliding and sliding friction dynamics: Grey box and black-box models Mech. Syst. Signal Process. 21(1) 514-534
[7] Schwingshackl C W, Petrov E P and Ewins D J 2012 Measured and estimated friction interface parameters in a nonlinear dynamic analysis Mech. Syst. Signal Process. 28(1) 574-584
[8] Lim S C, Ashby M F and Brunton J H 1989 The effects of sliding conditions on the dry friction of metals Acta Metall. 37(3) 767-772
[9] Wakuda M, Yamauchi Y, Kanzaki S and Yasuda Y 2003 Effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact Wear 254(3-4) 356-363
[10] Dai H-L, Dai T and Yan X 2015 Thermoelastic analysis for rotating circular HSLA steel plates with variable thickness Appl. Math. Comput. 268 1095-1109
[11] Shon S, Kahraman A, LaBerge K, Dykas D and Stringer D 2012 Influence of surface roughness on traction and scuffing performance of lubricated contacts for aerospace and automotive gearing Proceedings of the ASME/STLR International Joint Tribology Conference (USA: ASME) IJTC2012-61212 pp 87-89
[12] Kang Y S 1997 Friction identification in a sight stabilization system at low velocities Mech. Syst. Signal Process. 11(3) 491-505
[13] Povey T and Paniagua G 2012 Method to improve precision of rotating inertial and friction measurements in turbomachinery applications Mech. Syst. Signal Process. 30 323-329
[14] Novak R and Polcar T 2014 Tribological analysis of thin films by pin on disk: Evaluation of friction and wear measurement uncertainty Tribol. Int. 74 154-163
[15] Velkavrh I, Lüchinger M, Kern K, Klien S, Ausserer F, Voyer J, Diem A, Schreiner M and Tillmann W 2017 Using a standard pin on disk tribometer to analyses friction in a metal forming process Tribol. Int. 114 418-428
[16] Torre Pérez A, Garcia-Atance Fatjó G, Hadfield M and Austen S 2011 A model of friction for a pin on disk configuration with imposed pin rotation Mech. Mach. Theory 46 1755-1772