# Magneto-Electric Behavior of a Dynamic Couple of Paramagnetic / Ferromagnetic Materials

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## Abstract

The tribological behavior of a pin of paramagnetic material (aluminum), rolling on a rotating disk made of ferromagnetic material (steel XC48) in the presence of an externally applied alternating magnetic field, with the passage of electric current were studied. All tests were performed using a conventional tribometer pin- disk. The magnetic field is delivered by a coil of 500 turns. The normal load applied varies from 60 to 180 N. The sliding velocity was kept constant and equals 0.38 m / s. The interface is driven by an electric current continuously varying from 0 to 40 A. The simultaneous presence of electric current and magnetic field cause a decrease in the coefficient of friction and the amplitude of its fluctuations. In the presence of electric current, the wear of the pin aluminum decreases gradually when the values of the magnetic field becomes large enough. The analysis of the worn face of the pin, by a scanning electron microscope, showed the influence of magnetic field on the oxidation degree of non-ferromagnetic material.

Structural characterization of the surfaces in contact, oxides and wear debris, by X-ray diffraction ($\theta$-2$\theta$ angle), showed the significant effect of magnetic field on the activation of the contact surface of the pin in no ferromagnetic material. The absence of the magnetic field causes a change of wear mode, and there is a transition from mild (oxidation wear) to a severe abrasive condition. Moreover, the passage of electric current induces an electric field which also activates the growth rate of the oxide layer on the rubbing surfaces, but to a lesser extent in the presence of magnetic field. Therefore, the simultaneous effect of the magnetic field and electric current is identical to that of the magnetic field when applied alone.

**Keywords:** Friction, magnetic field, oxidation, surface, wear, wear by oxidation.

## 1. Introduction

The magneto-tribological interaction of materials in the presence of the magnetic field has been studied by many researchers such as [1] [2] [3] to name a few, but most of the comments focused only on the apparent wear surfaces. Indeed, the presence of the magnetic field in ferromagnetic/ferromagnetic contact significantly modifies the tribological behavior with a consequent reduction of the wear [4] [5]. While there is an increase of the latter for a pin in no-ferromagnetic material. The coefficient of friction μ of the contact has a relevant attractive interest [6] because it decreases with the presence of applied magnetic field. The analysis of the worn face of the pin, by Scanning Electron Microscope, showed the influence of magnetic field on the oxidation with a transfer of material from no-ferromagnetic material to the ferromagnetic. Structural characterization of the contact surfaces, oxides and wear debris, by X-ray diffraction (θ-2θ angle), showed the effect of magnetic field on the activation of the contact surface of the pin material non-ferromagnetic [7].

## 2. Expérimental Conditions

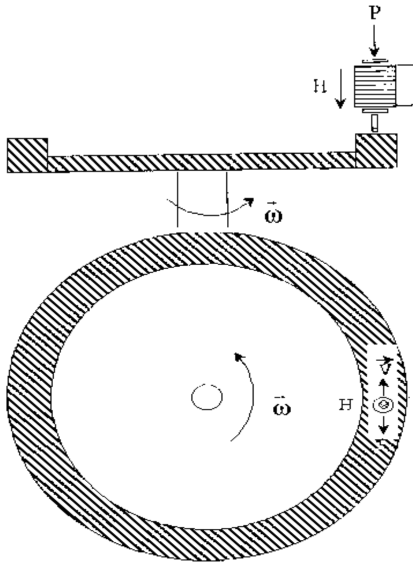



**Figure 01**: Schematization of the experiment principle.

The experiments were performed in the ambient air on classical pin-disc tribometer. The ferromagnetic steel XC48 disc with a radius of 130mm and the pin in non-ferromagnetic material (aluminum), it is cylindrical with 100 mm in length and contact area with a diameter of 10 mm. In each test, the surfaces of the disc and the pin are carefully polished (Emery Paper Grade 1200) to remove impurities and thus maintain the same experimental conditions, with a good finish of the contact surface in successive trials. The sliding contact duration is 30 minutes under different normal loads P, and a relative speed of sliding v = 0.38m / s. The magnetic field H, intensity ranging from 0 to 18 kA / m, is issued with a coil of 500 turns carried by the pin (Fig. 1). The piece is weighed with a microbalance before and after sliding, and its wear W is deduced from its mass loss.

The debris ejected from the contact has been studied by a diffract meter (θ-2θ angle). As for the contact surface of the pin rubbed with or without the presence of the magnetic field is discussed in Scanning Electron Microscope (SEM).

## 3. Results and Discussion

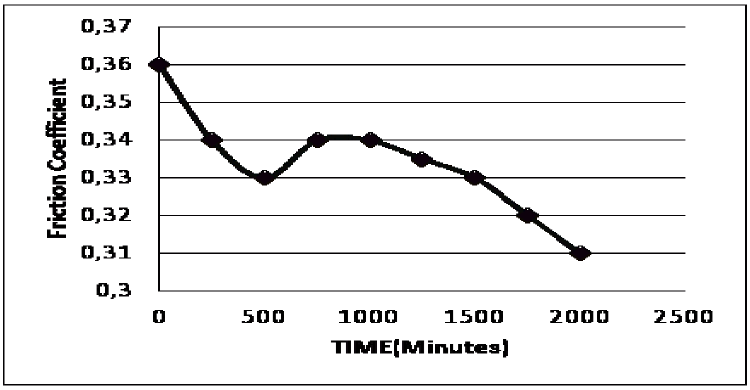
### *3.1 Antagonists Materials*

**Table 1**

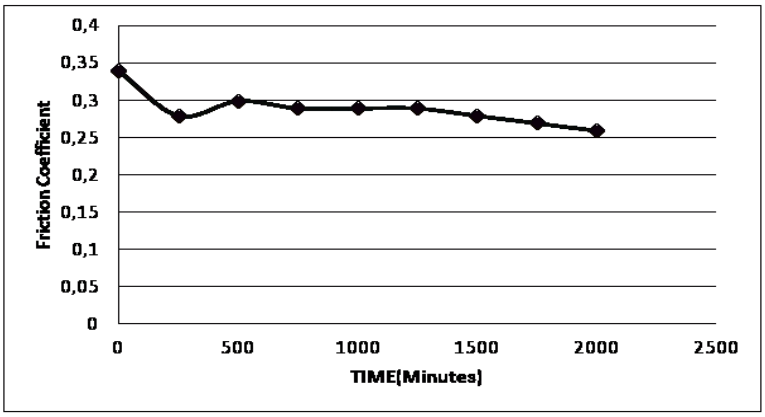
| Matériaux | Composition chimique (%) |
|---|---|
| Acier C48, nouvelle nuance C45E | C 0.45-0.51 Mn 0.50-0.80 Si 0.10-0.40 S=0.035 P=0.035 |
| Aluminium pur | > 99 % |

### *3.1.1. Friction Coefficient*

The coefficient of friction for the torque aluminum / steel XC48 has fairly stable average values at the beginning of sliding. Nevertheless the coefficient of friction is stabilized around 0.3 for H = 0 (a) and around 0.26 for H = 18kA / m (b).




**(a)**

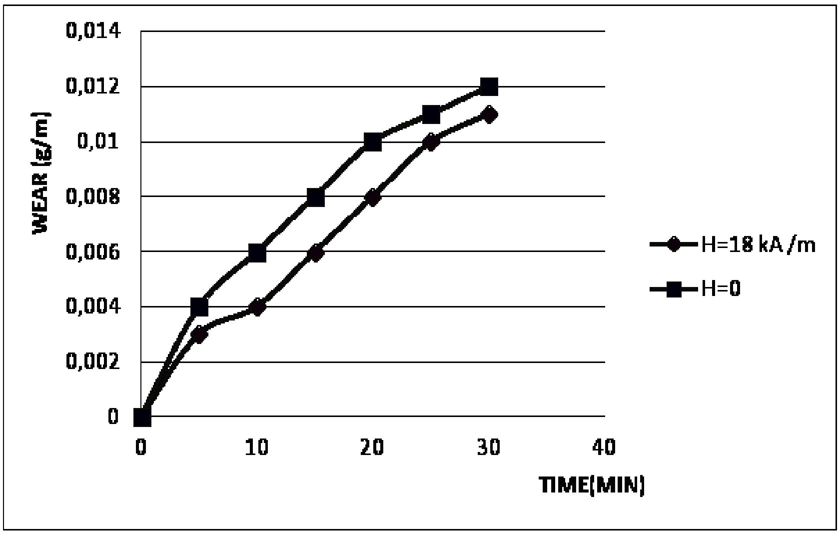



**(b)**

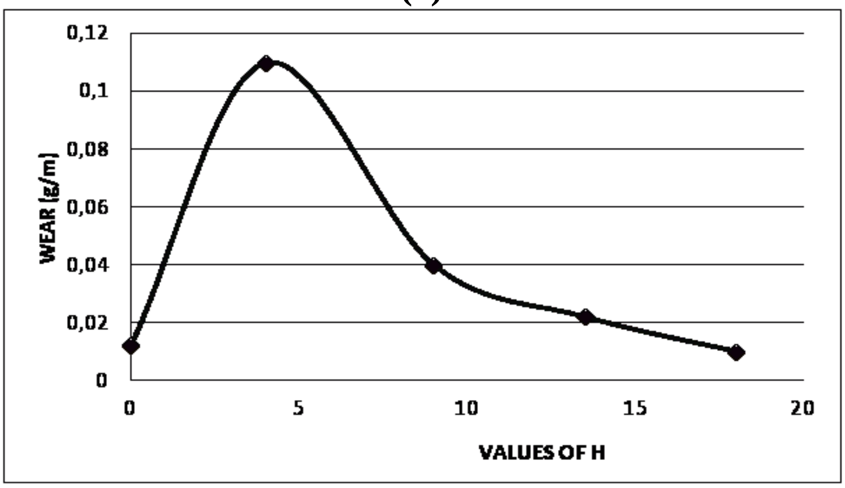
**Figure 02**: Change in coefficient of friction as a function of time, I = 10A, v = 0.38m / s, P = 180N and a magnetic field strength: (a) H = 0 and H = 18 [kA / m] (b).

### *3.1.2. Influence of Magnetic Field Intensity on the Wear of The Couple.*

The wear of the pin shows that an aluminum looks almost identical in the two cases where H = 0 and H = 18kA / m Fig.03 (a). The evolution of the wear, according to H, shows an increase for low values of the field, and then decreases for high values of H Fig.03 (b). This phenomenon is interpreted by the increase in metal oxidation in the presence of a magnetic field, which favors the creation of very hard free particles ($Al_2O_3$). Indeed it has a track without blackened particles Fig. 04 (a), whereas with H = 18kA / m, one notices their presence Fig.04 (b).

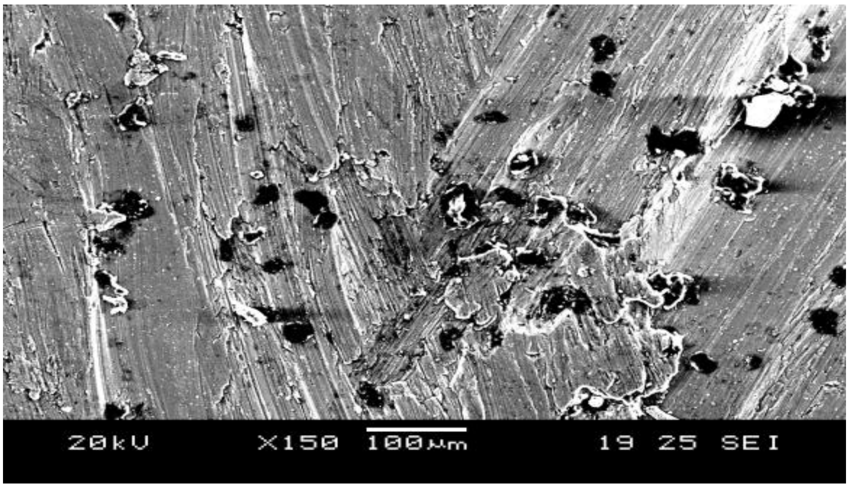



**(a)**

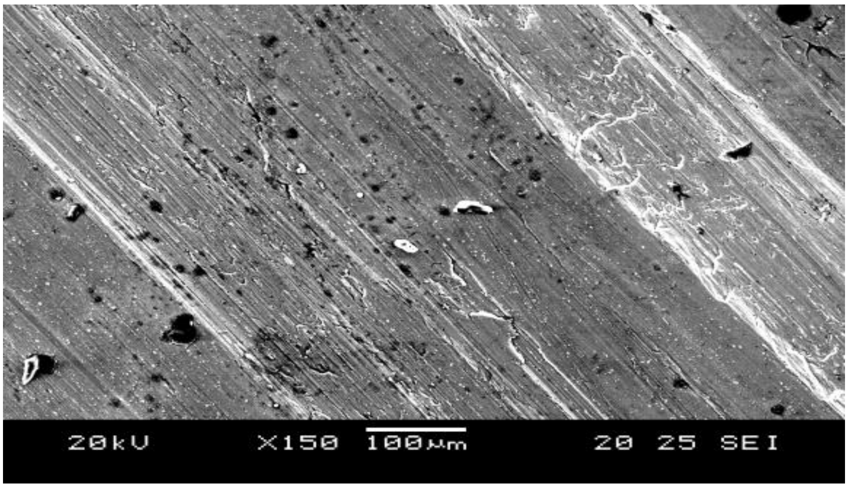



**(b)**

**Figure 03**: Variation of the aluminum wear checker as function of time, I = 10A, with and without magnetic field for: t = 30 min, v = 0.38 m / s, P = 180N (a), Evolution of the wear according H (b).




**(a)**




**(b)**

**Figure 04:** Photographs by M.E.B. showing the worn surface of the aluminum piece, I = 10A, for H = 0 (a) and for H = 18kA / m (b).

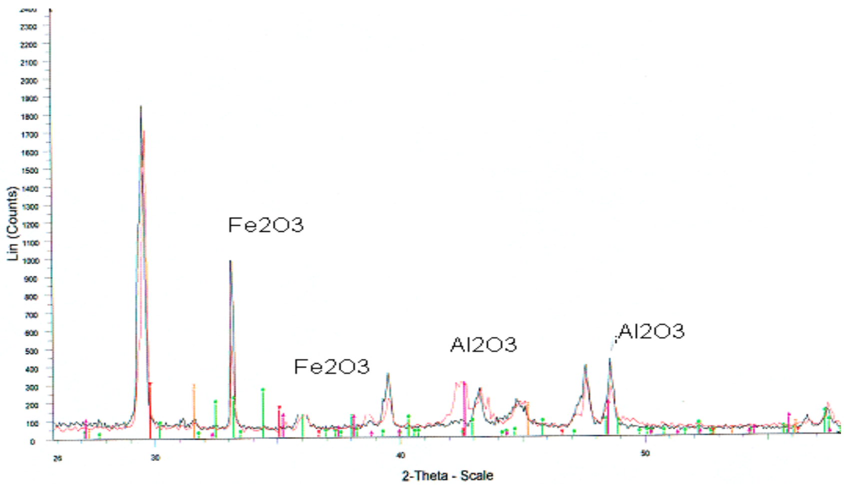



**Figure 05**: Diagram of X-ray diffraction (θ-2θ) wear debris of steel-aluminum couple XC48 rubbed having 30 minutes in an air atmosphere under the following conditions: v = 0.38m / s, I = 10A, (a) H = 0(dark color) , (b) H=18kA/m(red color).

**Discussion**

Figure 02 (a), (b) illustrate the evolution of the friction coefficient of the torque piece aluminum-steel disc XC48 versus time with and without the presence of a magnetic field, and with passage of electrical current. Indeed, these results obtained in our experimental conditions show that the friction coefficient decreases with a value of 0.3 with no magnetic field to the value 0.25 in its presence. This is due to the presence of small black particles of oxidation under the effect of the magnetic field. The birth of these particles leads to the transition from severe wear to mild wear.

In Figure 03 (a), we see the curve of the wear over time takes almost the same proportions with and without magnetic field with electric current passage. Figure 03 (b) tells us about the evolution of the wear according to the values of H. Indeed, for values of H ranging up to 13.5 kA / ml wear is substantial compared to that given for a magnetic field equal to 18 kA / m. Indeed this can be explained by severe wear, which settles for small values of H. For the value of H = 18 kA / m, there is a genesis of black oxide film that forms at the beginning of the friction in a magnetic field, the thickness of the oxide layer increases until the track total coverage contact with an extremely thin layer of oxide and black pawn on the trail of the XC48 steel disc after a few cycles of sliding, which play a protective role fig. 04 (b), and decreases wear.

The observations of the SEM photographs given by Fig.04 of the surface state of the pin and aluminum X-ray diffraction analysis (θ-2θ) Fig.05, wear debris recovered on the slopes of the friction torque of the aluminum and the steel XC48, show that the wear-free magnetic field is purely abrasive (Fig.04 a). Whereas the presence of magnetic field reveals, in the figure 04 (b), black oxide debris forming the third body. The formation of this layer and its thickness is a function of the magnetic field strength and the applied mechanical load; these phenomena correspond to a competition between various processes acting on the track contact during friction.

The ejected particles from the contact form as a variety of oxides, $Fe_2O_3$, $Al_2O_3$, and AlO as shown figure.05 which is a superposition of two spectra. Indeed, for H = 0, we have a first spectrum (red), the second for H = 18 kA / m (black). Presumably, the pace of the two spectra is the same except that the percentage of elements forming the debris ejected from the contact and higher in the presence of magnetic field.

**Conclusions:**

The experimental study that we conducted on the tribological behavior of the torque non-ferromagnetic / ferromagnetic dry contact sliding aluminum / steel XC48, subjected to an alternating magnetic field crossed by an electric current brought us to some conclusions:

The friction coefficient decreases in the presence of electric current and magnetic field.

The structural characterization of the oxidation surfaces of the wear debris by XRD
($\theta$-$2\theta$) highlighted the influence of magnetic field on the activation of the oxidation of the contact surface of the pin non-ferromagnetic. The wear mode changes from abrasive wear without magnetic field by oxidation in its presence.

The formation of oxide film on the black track on the disc is the main phenomenon that affects the tribological behavior of contact magnetized protecting the aluminum surface against wear.

The oxide film reduces the shear force at the interface, facilitating slippage. The film adheres to the contact interface and different morphologies appear, it changes the rheology of contact by reducing the frictional force in contact, facilitates sliding and reduces damage due to plastic deformations

the presence of the magnetic field increases the pressure of molecular oxygen around the tribocontact,

the oxide layer deposited on the pin, permitted to the deep junctions of the disc to be in contact with the pin, which leads to new contact joints after each round slippage.

The passage of electrical current through the contact increases the interface heat generated by the birth of eddy currents, which also activates the oxidation of contact surfaces, but of a lower order than the activation induced magnetic field. The simultaneous effect of the magnetic field and electric current is virtually identical to that of magnetic field alone.

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