

EFFECT OF ELECTRICAL CURRENT ON FRICTION AND WEAR BEHAVIOR OF COPPER AGAINST GRAPHITE FOR LOW SLIDING SPEEDS

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Copper-graphite is an important tribological material used in the applications of electrical sliding contact like generators and electrical brushes. A series of experimental tests were conducted on a pin-disc tribometer in air and dry sliding condition. The pair of material was subjected to electric current ranging from 0 to 10A, normal loads of 5 to 30N and sliding speed of 0.5m/s. The duration of each test was 30 minutes. Experimental results indicated that the friction coefficient decreases and wear rate increases with increasing load with and without applied electric current. The changes in surface chemistry and topography of the tribo-surfaces were characterized using Raman spectroscopy, scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS). This later technique was used to analyze the transfer of pin materials to the counterface, and also to understand how copper and graphite influence the tribological properties. Results indicated that, electric current and normal load have more or less significant influence on the tribological behavior of the pair of materials and the effect of oxide layer created at interface of the pairs in contact.

Keywords: Friction, Wear, Contact temperature, Load, Electric current.

1. Introduction

Friction is one of the oldest and most important problems encountered in the engineering applications. It is a very complex process related to mechanical, thermal, physico-chemical, metallurgical factors. This phenomenon becomes a heat generating source which causes a local temperature rise at the interface of the two materials. Mechanical energy dissipation at the interface due to friction is proportional to the applied load and the sliding speed antagonists, and becomes a heat source. In the case of sliding electrical contacts, there are several sources of heat dissipation such as dissipation due to friction, dissipation by Joule effect and under certain conditions the dissipation due to the increased temperature from electric arcs effects [1]. The resulting increase is able to affect the properties of the facing material and the interfacial characteristics of the elements and modify, in some situations, their surface structure.

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Frictional behavior mainly governs the properties of the component surfaces to improve their wear and corrosion resistance and thus reduces friction. Several models have been developed in order to explain this behavior [2]. A number of papers [3-6], show that friction and wear behavior were largely depends on the normal load, sliding speed, electrical current, type of materials, geometry, relative humidity, lubrication and vibration. Several investigations confirm that the applied electrical current reduces the friction coefficient of sliding contact couples. This decrease was attributed to an oxidation film formed on the contact surfaces caused by Joule heat, friction heat and arc discharge heat [7,8]. The local increase of the contact temperature caused by heating can have an important influence on the tribological behavior and favored the oxidation [8,9].

Copper-graphite couple is an important tribological material combination used in electrical sliding contact applications such as brushes in electrical motors and generators. The strategy for choosing a tribological test method will depend on the expected results and defined by the test under consideration [10,11]. This strategy can begin with a theoretical basic research on physical process involved. Pin on disc tests are generally used in order to evaluate the tribological performance in laboratory scale [2]. In the present study, the objective is to investigate the effect of the applied load and electrical current on the friction and wear behavior of the tribological couple copper-graphite under dry sliding conditions for lower sliding speeds. The effect of oxide layer formed at the interface of antagonist, on the behavior of friction and wear are also presented.

2. Experimental details

Friction tests were was performed on a pin-on-disc test under ambient conditions. The schematic of the tribometer is shown in **Fig.1a**. Experimental test was effectuated under different loads (5, 10, 15, 20, and 30 N), electrical current (0, 3, 6 and 10A) with a sliding speed of 0.5m/s and 30 minutes for each test. As illustrated in **Fig. 1b**, the used pin has a cylindrical shape comprises a flat part which allows to fix it in a hole by means of a locking screw on a load arm. It is loaded against a disc by adding different weights successively. The pin is easily replaced by another sample, or can be removed to measure the mass loss. The tested disc is a circular plate fixed to a support which rotates at variable speed. The disc is driven by an a.c. electric motor through a 1:20 transmission ration gearbox. The frequency converter allows for a range of rotational speed from 10 to 240rot/min. The radius of the wear track is set to 0.02m; the linear velocity varies between 0.02 and 0.5m/s. The normal force is transmitted to the sample holder with the loads resting on the end of a load arm. The load on the pin does not exceed 40N. The discs have 50mm in diameter and 5mm thickness; the pins have 8mm in diameter and 20mm in length.

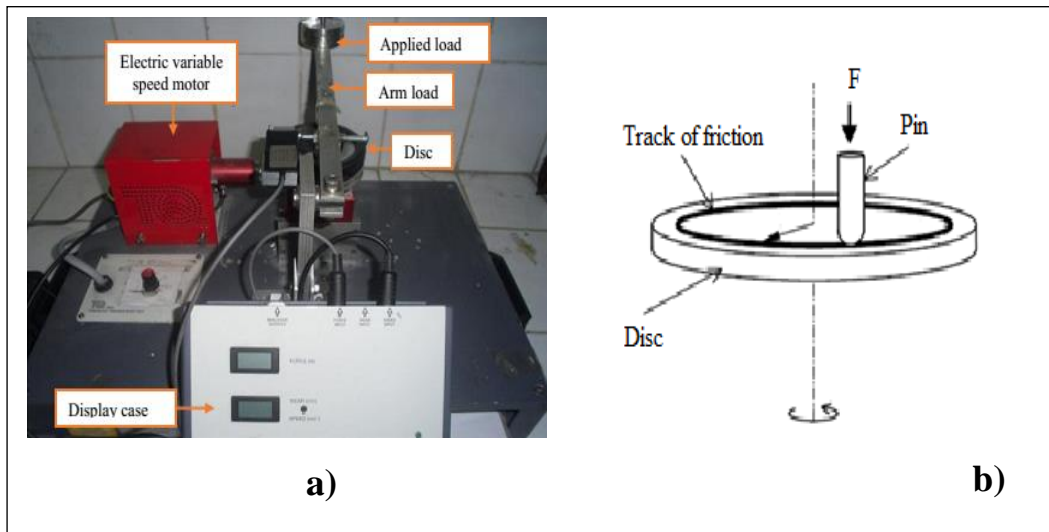


Fig. 1. a) Pin-on-disc tribometer, b) Scheme of the pin-disc contact

The force sensor records the friction force produced between the two samples by an acquisition system (3D piezoelectric sensor). The friction coefficient is defined as the ratio between friction force developed in the direct contact of the two surfaces obtained by a data acquisition system divided by the normal force.

The surface temperature of the contact strip was measured by a K-type thermocouple placed inside the surface pins at 2mm behind the friction. The measured temperature is not exactly that of the contact surface, but it is a good indicator of variation of contact temperature. Pins wear is evaluated by the weighing method using a balance of precision 10^{-5} g. On each test, the sample is weighed before and after wards.

In the tests, the sliding speed is 0.5m/s and the duration of each test is 30 min. The normal forces were selected to be 5, 10, 15, 20 and 30N and electric current was selected to be 0, 3, 6 and 10A.

The pin is a pure copper (99.9 %) known to be a good conductor of heat and electricity. The disc is made of electro-graphite under commercial name DE9000. The physical properties of the materials are presented in Table.1

Table 1

Characteristics of materials

| | ρ [kg/m ³] | λ [W/ (m.°C)] | Cp [J/ (kg.°C)] | σ [$\Omega^{-1} \cdot m^{-1}$] |
|----------|--------------------------------|--------------------------|--------------------|--|
| Copper | 8900 | 386 | 384 | $6 \cdot 10^7$ |
| Graphite | 1900 | 164 | 754 | $1,25 \cdot 10^3$ |

The morphology of contact surface was observed by an optical microscope (OM) G-120A stereo binocular. We used scanning electron microscopy (SEM) ZEISS EVO-MA25 to study the worn surface and Energy Dispersive X-ray OXFORD instruments X-MAN^N 80 (EDS) for analyzing the surface films composition. Also the profiler AltiSurf 500 was used to measure roughness.

3. Results and discussions

Raman spectrometry is an important tool to analyze the vibrations bands of the prepared material. **Fig. 2** shows the Raman spectra of the copper-graphite couple at different values of electric current 0, 3, 6 and 10 A. All graphite Raman peaks are represented in the spectra (**D**, **G**, **D'** and **2D**).

D and **G** bands are localized around 1350 and 1587 cm⁻¹ respectively. The first vibrational mode is caused by disordered structure of graphite. The second vibrational mode is related to the E_{2g} phonon at the Brillouin zone center which results in the stretching of the C-C bond in graphitic materials [12, 13].

D' band which localized at 1620 cm⁻¹ is the result of the interaction between the localized vibrational modes of copper impurities and the extended phonon modes of graphite as proposed *Stephanie Reich* [13].

The band **2D** at around 2735 cm⁻¹, it is the second most noticeable peak always observed in graphite samples. *Stephanie Reich and Christian Thomsen* [13] reported that this band is the result of the two phonons with opposite momentum near the K point.

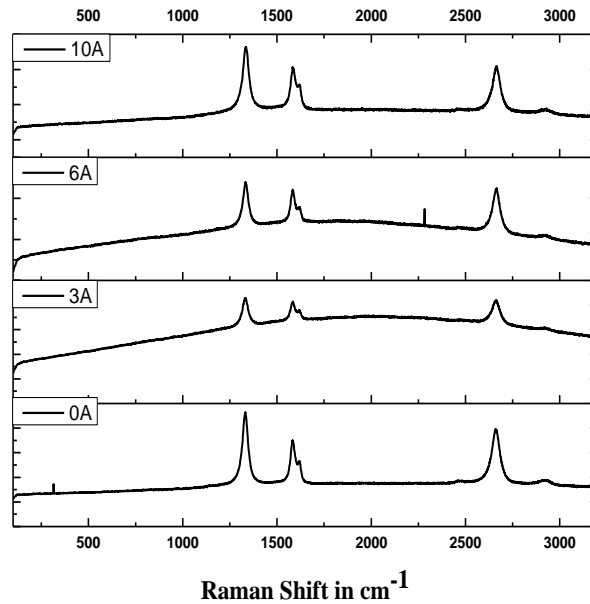


Fig.2. Raman spectra of copper-graphite couple

3.1. Effect of current and load on friction, contact temperature and wear behaviors

Fig. 3 shows the variation of the friction coefficient and contact temperature of copper-graphite couple versus duration of rubbing, with and without electric current, under dry conditions, for fixed applied load of 20N and sliding speed of 0.5m/s. The curves presented in **Fig. 3a** show the existence of two friction regimes as reported in literature [14,15]. The first is characterized by a sharp increase (running-in period) which lasts about 2 minutes, and then a gradual decrease is followed by a steady-state value after transient period. The steady-state of friction coefficient depends on the stability of the conditions at the interface (number of wear particles torn off becomes constant). Friction coefficient of dynamic contact without electric current illustrated in **Fig. 3a** shows a sharp increase after the start of the experiment, and then the increase becomes moderate until reaching asymptotic values after several minutes. This indicates that evolution of friction coefficient with and without applied electric current is similar. It can be noticed also that the friction coefficient with applied current is smaller than without applied current, because an oxidation layer created due to the applied electric current plays a role of lubricant at the interface. Similar

behavior was obtained by Wang *et al.* [16] for sliding speeds of about 7m/s. The variation of contact temperature surface with time for different applied electric current is shown in **Fig. 3b**. It is observed that the contact temperature of copper-graphite materials increases rapidly at the beginning of the experiment and then increases slowly to become stable after about 15 minutes. It can be observed that when the intensity of electric current applied is greater, the contact temperature of tribological couple is higher. For example, without applied electric current ($I = 0A$), the asymptotic value of the stable temperature is about $54^{\circ}C$. However, for a maximum applied electric current ($I = 10A$), the asymptotic value of the stable temperature is much higher and equal to about $148^{\circ}C$.

In the presence of electric current, it can be seen that the contact temperature increases significantly and the production of sparks observed at the interface of the frictional pair in test takes place in the process of electric sliding friction. The combination between Joule heats, friction heat and arc discharge leads to fast increase in the temperature of contact [3].

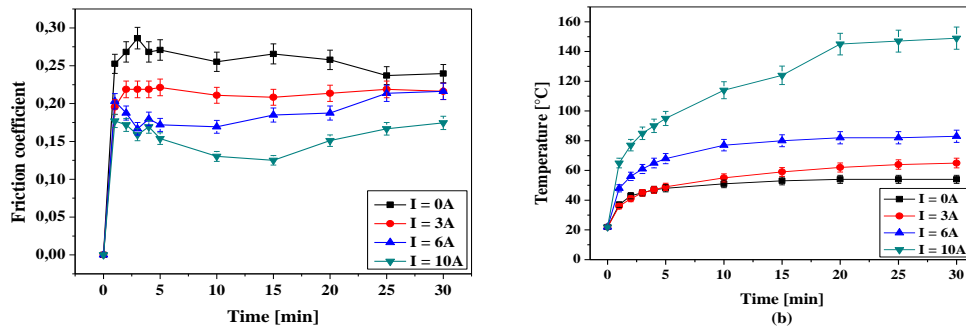


Fig.3. Friction coefficient and contact temperature in air with different current versus time ($P = 20N$ and $V = 0.5m/s$)

Fig. 4 shows the evolution of the friction coefficient, wear rate and contact temperature as a function of normal load in ambient conditions at a sliding speed of 0.5m/s with and without applied electrical current. At lower load value of about 5N as shown in **Fig. 4a**, maximum values of the friction coefficients are obtained for both cases. In this case, contact asperities and entanglement increase the adhesion between antagonists and the shear stress at the interface. After this value, the friction coefficient decreases rapidly when the applied load increase from 5 to 15N and subsequently decreases slightly, when the applied load increased from 20 to 30N. Similar trend of the presented results in Fig.4a was obtained by Wang *et al.* [17] and Ding *et al.* [18] for higher range of applied sliding speeds. This is especially due to the mutual adaptation of the two contact surfaces in the two cases. Friction coefficient without applied electric current is greater than with applied current. This difference is due to the created lubrication film at the

interface of sliding contact under the presence of electrical current. This thin-film of oxide precludes the direct contact of antagonist surface and decrease the adhesion between frictional pair. Some work indicates that the oxide layer created at the interface by electrical current play a paramount role to reduce the friction coefficient [18,19].

Wear rate of contact strip increase with increasing of load in presence or absence of electric current as shown in **Fig. 4b**. Wear particles of copper is greater with the presence of electric current than that without current in the same applied loads. In the absence of electric current, under low load, the wear rate is substantially proportional to the load. Further increase in the load, lead to an increase of the tangential force. Mixed of debris constituted of copper and graphite particles trapped between the pin and the disc plow the copper surface and make severe deformation. Without applied electrical current, wear rate depend on the mechanicals wear only. The wear process is more complex with electric current because the process of sliding wear and the applied load increases the contact surface temperature due to the Joule heat, friction heat and arc heat [7]. These increases in the contact temperature affect the material properties which become softer, decrease the roughness of contact surface as shown in **Tab.2** and reduces the friction coefficient. In addition, the increased contact temperature accelerates material wear which facilitates the transfer of copper in the pits of strip surface of graphite. The increase of contact temperature and the softening of the material confirm that the increase of wear rate is caused by the abrasive mechanism of wear. The adhesive wear mechanism is inactive because the formation of ultra-thin film of oxide plays a role of lubricant in the presence of electrical current.

From **Fig. 4c**, it is clearly seen that the variation of temperature of the contact strip surface increase with increasing of load. The contact temperature increases rapidly with increasing of applied load at electric current of 10A. Without current, the value of contact temperature is kept roughly constant with increasing of applied load. At the same applied load, the contact temperature in the presence of electric current is significantly higher than the temperature without electrical current.

The evolution of friction coefficient as a function of electric current at a sliding speed of 0.5m/s and load of 20N is shown in **Fig. 5**. For 20N normal load, the friction coefficient decreases as the electric current increases. This is due to an ultra-thin film of oxide which plays the role of lubricant layer at the interface, as shown in Fig.8.

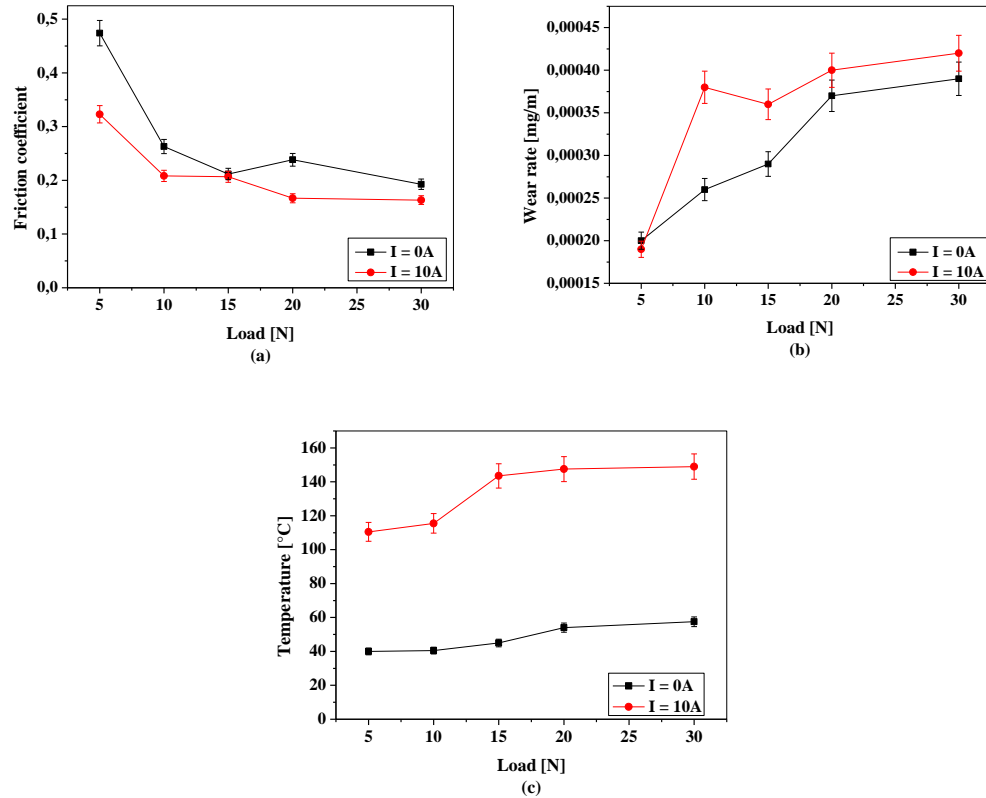


Fig.4. Friction coefficient, wear rate and contact temperature versus load applied for $V = 0.5$ m/s under $I = 0A$ and $I = 10A$

Due to the increase of the current intensity, the contact temperature increases by Joule effect and the formation of the oxide layer is activated (Fig.7 and Fig.8). The copper oxide, which plays a role of lubricant at the interface, can decrease the roughness of the strip friction and lead to a decrease in the friction coefficient and wear rate. The oxide and the material transferred filled in the pits between the asperities that will give a flat surface.

Table.2

Variation of copper roughness for $P = 20N$ and $V = 0.5m/s$

| Electric current (A) | I = 0 | I = 3 | I = 6 | I = 8 | I = 10 |
|-----------------------|--------|--------|--------|--------|--------|
| Roughness (μm) | 0.1557 | 0.1206 | 0.0682 | 0.0617 | 0.0416 |

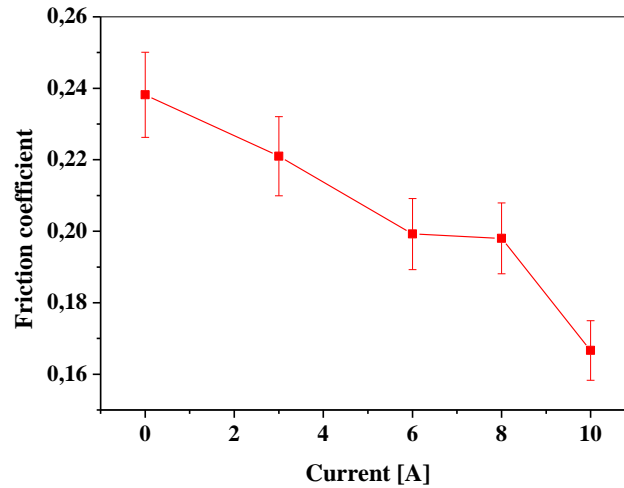


Fig.5. Evolution of friction coefficient versus electric current to $P = 20\text{N}$ and $V = 0.5\text{m/s}$

3.2. SEM observation and EDS spectrums of worn surface

To understand the tribological phenomena at the pin and disc interface, scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) were used to analyse the worn surface and the transfer of materials during test with different electrical currents.

Fig. 6a shows the SEM morphologies of worn surface of copper and **Fig. 6b** is a high magnification SEM image. It presents the surface of the pin after friction test of 30 minute without electric current ($I = 0\text{A}$). An important removal of material characterized by ploughing ridges in the sliding direction owing to rough surface. These ploughing are the result of the adhesive action between antagonists. EDS spectrum from **Fig. 6c** shows an important peak of copper with 72.57%. Some particles of graphite are transferred on the surface of copper pin under the action of mechanical wear with 27.43% of carbon and total absence of oxygen. The wear particles at the interface are oxides due to oxygen from the ambient air, with a little metal wear debris, which means that oxide film is immediately extracted under mechanical action because it has low shear strength. Abrasive wear, adhesive wear and material transfer are the mechanisms more dominant in the absence of electrical current. **Fig. 7** shows the SEM morphologies of worn surface of copper for $I = 3\text{A}$. Debris ripped due to dynamic contact and increasing of contact temperature by friction and Joule effect, are the parameters that affect the strength of the material. Due to the reduced resistance of materials pair, delamination occurs easily on contact strip. So, delamination and abrasion are the

dominant wear mechanisms in the case of low electrical current. Generation of oxidation layer is caused by the increase of contact temperature and EDS spectrum as shown in **Fig. 7c**. This generation of oxidation layer proved the presence of oxygen with 10.92% in the contact surface of copper pin.

If the electric current increases, the worn surface of the friction strip becomes smooth because the roughness decreases, see **Tab. 2**. An oxide layer is formed at the interface of the two surfaces rubbed but it does not remain all the time present, it wears with a wear mechanism when it reaches a critical thickness. **Fig. 8** shows the SEM morphologies with electric current $I = 10A$ of worn surface of copper pin. On the worn surface of friction strip, there are micro-cracks, grooves deep and spalling blocks. The fracture of flake-like delamination creates the third body friction. EDS spectrum from **Fig. 8c** shows, peaks of carbon with 61.03%, copper peaks with 25.15% and presence of oxygen peaks with 13.82%.

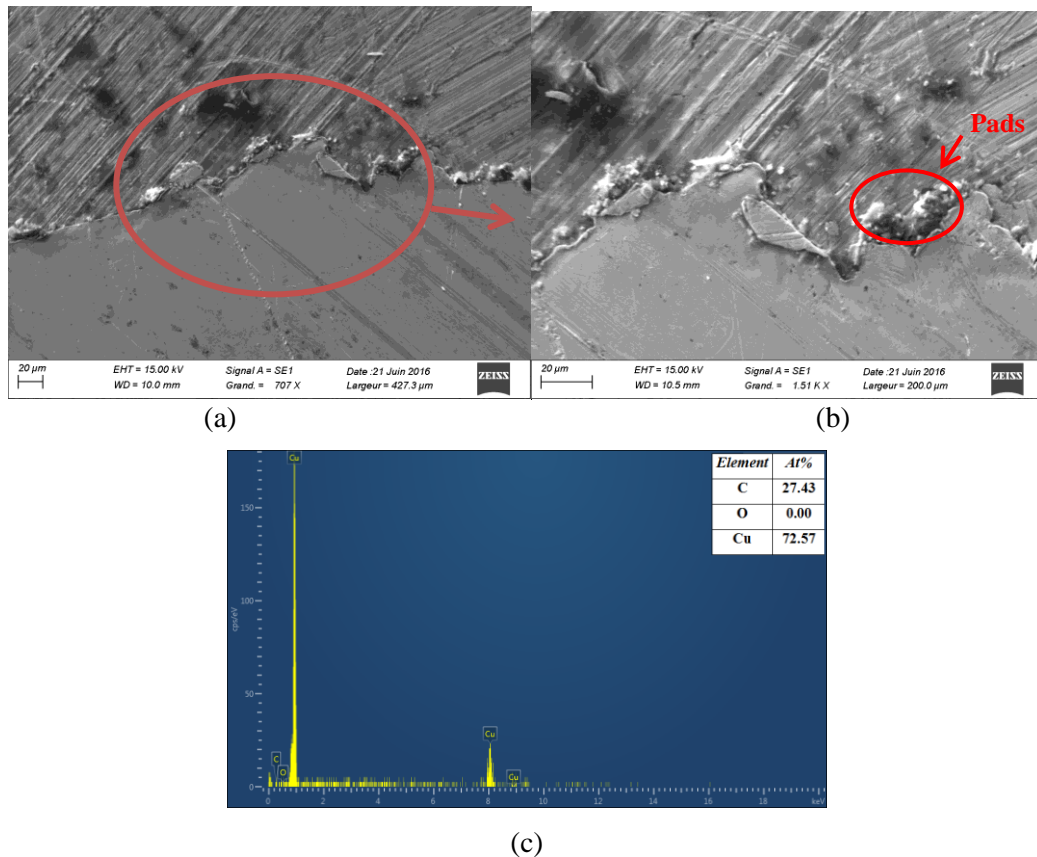
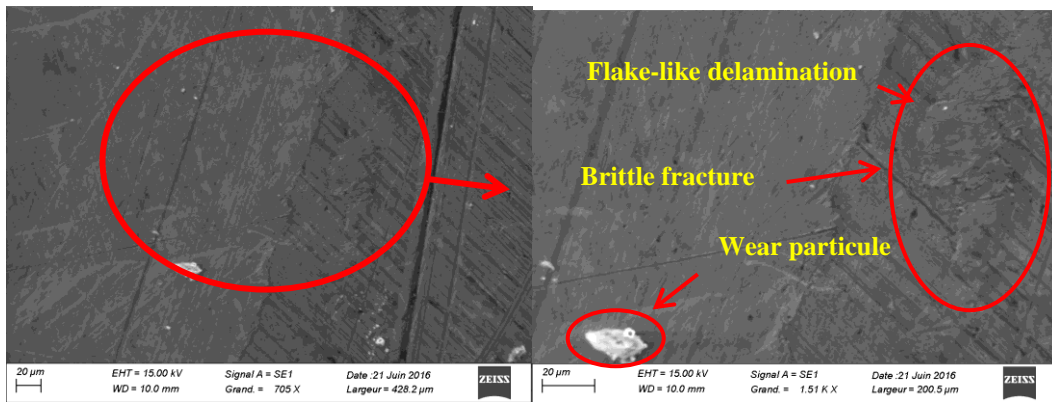
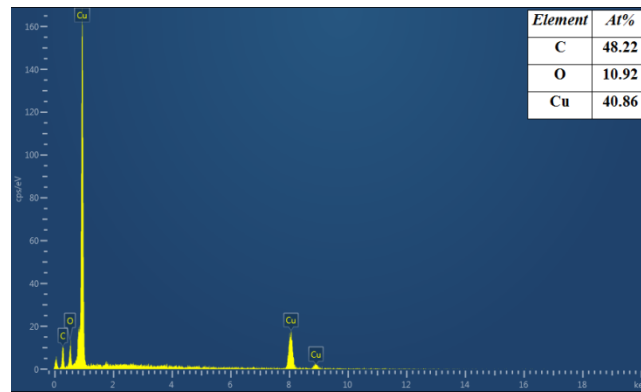


Fig.6. (a) and (b): SEM morphologies of worn pin surface for $P = 20N$, $V = 0.5m/s$ and $I = 0A$;
(c): EDS spectrum



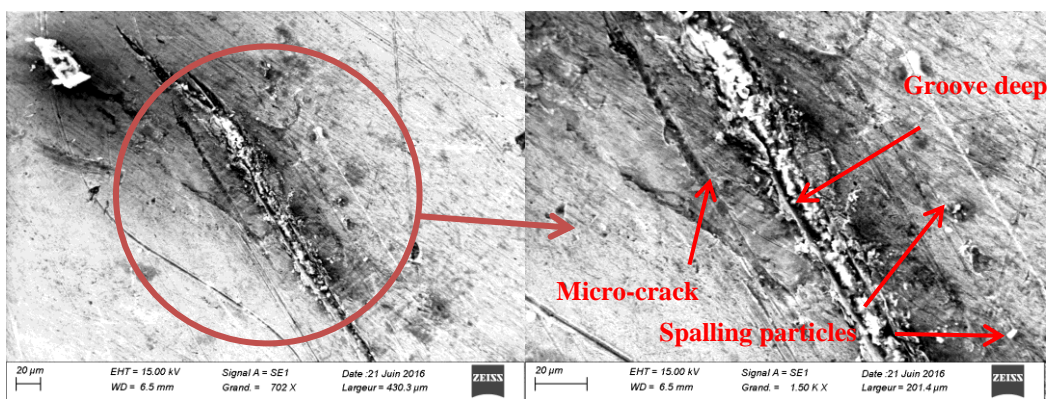
(a)

(b)



(c)

Fig.7. (a) and (b): SEM morphologies of worn pin surface for $P = 20\text{N}$, $V = 0.5\text{m/s}$ and $I = 3\text{A}$; (c): EDS spectrum



(a)

(b)

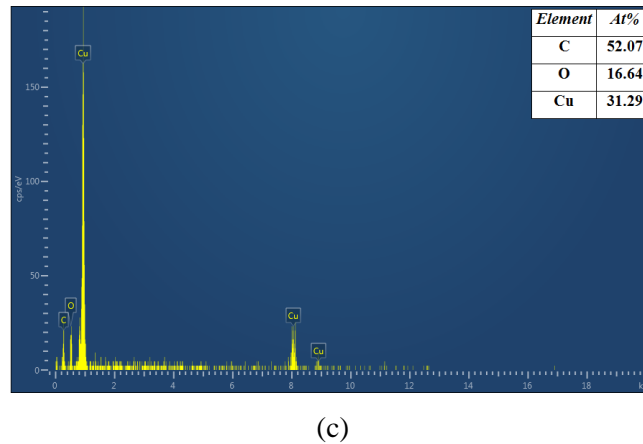


Fig.8. (a) and (b): SEM morphologies of worn pin surface for $P = 20\text{N}$, $V = 0.5\text{m/s}$ and $I = 10\text{A}$; (c): EDS spectrum

4. Conclusions

Several series of experimental tests were carried out using pin-disc tribometer in air and dry sliding contact for an electric current varying from 0 to 10A, normal loads between 5-30N and low sliding speed (0.5m/s). The changes in surface chemistry and topography of the tribo-surfaces were characterized using Raman spectroscopy, scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS). Different conclusions can be drawn from the present study and summarized as follows:

- (1) Friction and wear behavior for low sliding speed in the presence of electric current is similar to the case of high sliding speeds; friction coefficient decreases when the intensity of electric current increases.
- (2) With and without applied electric current, wear rate of copper increases with increasing normal load, and without applied electric current is lower than the case of applied electric current.
- (3) In the presence of electrical current, delamination, abrasive and oxidative wears are dominant wear mechanisms for the dry sliding contact demonstrated by SEM analysis and the adhesive wear mechanism is active for the case without current.
- (4) The formation of ultra-thin film of oxide plays a key role in reducing the friction coefficient for the case of electrical sliding contact.

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