Tribological Behavior of a Contact Pin on Cylinder CuSn7 Bronze Rubbing Against 20MnCr5 Steel in Dry Sliding with Electrical Current

Bekhouche Djamel, Bouchoucha Ali*
Laboratoire de Mécanique, Département de Génie Mécanique, Faculté des Sciences de la technologie, Université des Frères Mentouri Constantine 1, Constantine 25000, Algeria
**djamel.bekhouche@umc.edu.dz*

Zaidi Hamid
Institut Pprime, DGMS, Université de Poitiers, SP2MI, Bd Pierre et Marie Curie, BP 30179, 86962 Futuroscope Chasseneuil Cedex, France

ABSTRACT

The tribological behavior of CuSn7 Bronze and Steel 20MnCr5 couple was studied as a function of mechanical and electrical parameters and the contact geometry (pin on cylinder) under ambient environment. To do this, a pin on cylinder tribometer (the test machine is a kind of pin-on-slip ring) was used. Experimental results show that these parameters have a significant effect on the friction and on the wear. Indeed, the load has a significant influence on the tribological behavior of the couple both with and without electrical current. In the other hand, the friction coefficient and wear of the pin against the cylinder decreases especially at high values of electrical current. Moreover, the observed wear mechanisms are: adhesion, abrasion, oxidation, arc erosion and plastic deformation. At high applied electrical current and loads, the main wear mechanism is the arc erosion and severe plastic deformation. The discussion of the obtained results is based on examination of the worn surfaces and analysis performed on interfacial phenomena observed during the friction process.

Keywords: *Bronze, Contact Geometry, Adhesion, Oxidation, Arc Erosion, Altisurf Profelometer.*

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Introduction

The friction and the wear are dependent on several tribological parameters, which are interdependent on each other like normal load, sliding speed, hardness of the material, electric current, contact geometry, etc [1]. This makes the study of friction and wear in the laboratory more specific, since it is difficult to reproduce experimentally, the same conditions as those in which evolves in industrial equipment. There are many tribological test methods [2], the most commonly used for fundamental studies are laboratory tribometers such as: pin on disc test, block on cylinder test, unidirectional test or alternated movement on a plate test and test of four balls. In addition, the tribological behavior of couples contact materials also depends on films present at the interface [3]. These phenomena are complex, dependent on the external conditions and vary greatly from one material to another [4].

The surfacing films are the result of complex physical and chemical processes, including transfer of matter, debris generation and oxidation of materials. These films have unique lubricating properties and electrical characteristic [5]. In fact, the heat generated by the contact can increase the interfacial temperature, which favors the oxidation process [6]. Thus oxide films formed also play a significant role in wear and friction behavior of the materials. The works [3, 7] showed that the surface oxide films are beneficial to the process of friction and wear. However, in some cases where the oxide debris detach from the surface, they can act as an abrasive wear [8, 9].

The careful choice of materials antagonists and the optimization of operating conditions enable a longer life of the couple and decrease the number of posed problems [10].

The present study is different from most investigations on the tribological behavior of materials. Although, much works have focused on the tribological behaviors of materials with a pin-on-disc tribometers. The aim of this study is to investigate the tribological behavior of CuSn7 bronze sliding against 20MnCr5 steel with a new pin-on-cylinder machine (a block-on-slip ring type wear) with the application of some mechanical and electrical parameters.

Experimental details

Apparatus and specimens

Since it is not easy to reproduce the real conditions, even at a small scale, the study was implemented by adapting a pin on cylinder (a block-on-slip ring type wear) contact system mounted on a metal lathe type (SUMORE, SP2124-II). Figure 1 shows the principle diagram of the tribometer, while the structure is shown in Figure 2. The pin specimen used for the test was fixed in an insulated upper sample holder (in the arm of the tribometer). Another pin was mounted in the lower sample holder to conduct the electrical current. The pins were connected to the DC power, the upper in the negative terminal and the lower to the positive one. Dead weights were used to obtain a regular normal load between the two specimens. The rotation of the disc is provided by the mandrel of the lathe.

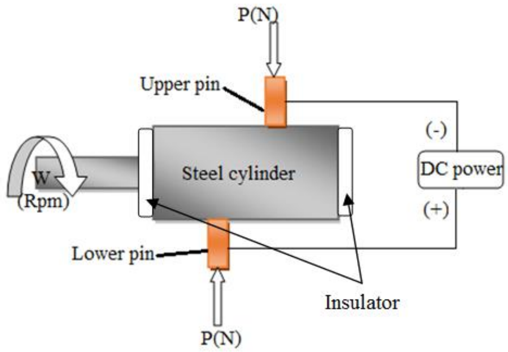


Figure 1: The principle of the test machine.

The disc specimen was made from steel 20MnCr5, its diameter is 45 mm. It is mounted on a disc holder fixed in the mandrel of the lathe. The pin supported against the cylinder by a normal load P, it has a cylindrical form with a diameter of 8 mm and a length of 20 mm. The pin specimen was made from CuSn7 bronze.

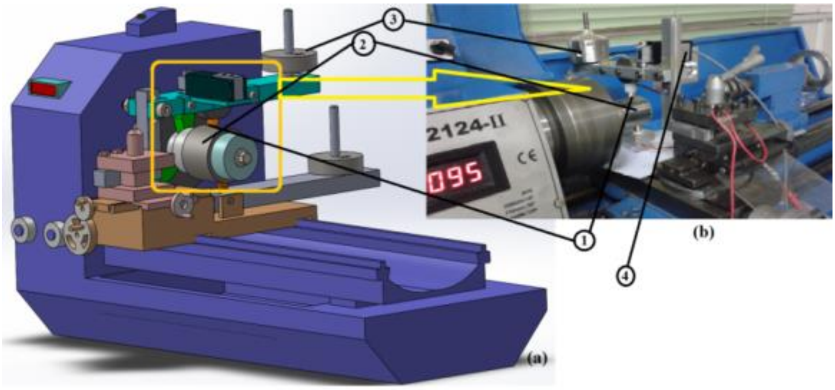


Figure 2: (a) Representation 3D of the test machine, (b) real figure test machine, 1 Pin, 2 Disc, 3 applied load, 4 force sensor.

Test procedures and parameters

Before each test, the steel surface was polished with an abrasive paper of a grade between 800 and 2000, and was cleaned with alcohol. The pin specimen on bronze was polished with abrasive paper of grade 1200 to get a good surface contact (roughness arithmetic R_a in the range of 0.32 to 0.48 µm). The tests are carried out under ambient air environment. The ambient temperature was about 22°C in dry conditions (without lubrication). The applied normal loads P were given as P = 7, 15, 18, 23 and 33 N (using dead weights), the sliding speed V was set as V = 2.3 m/s. On the other hand, the electrical current values were 3 A, 6 A, 8 A and 10 A. The time of each test was designated as T = 2400 s.

Measurement methods

The resulting tangential force of the contact was measured by a force sensor fixed on the arm of the tribometer. It was collected by a data acquiring system. The display of the results is provided with Cassylab software, version 2.0. The friction coefficient µ is obtained by the ratio of the tangential force and the normal force ($\mu = F / P$). Before the tests, the force sensor was calibrated by applying a series of dead weights. The wear volume of the pin was measured using a microbalance of 10^{-5} g of precision.

Statistical calculations

As shown in table 1, the tribological experiments were performed by varying the normal load in the range of 7 to 33 N, and the electrical current in the range of 0 to 10 A. Each test was repeated from two to three times in the same measurement conditions to verify the reproducibility.

Table 1: The Statistical calculations

Parmetre	Value
Pin	Cu Sn 7 Bronze
Cylinder	Steel 20MnCr5
Normal load	7 to 33 N
Sliding speed	2,3 m/s
Duration of test	2400 s
Electrical current	0 to 10A
Ambient temperature	22 °C
Humidity at ambient temperature	50-60 %
Lubrication	Dry conditions

Materials

The used materials were steel 20MnCr5 and Cu Sn7 bronze. 20MnCr5 steel is a carburizing steel with low carbon and chromium content, he has good resistance to wear and to fatigue. He is recommended for gearboxes and axle gears [11, 12]. In the other hand, CuSn7Pb6Zn6 bronze can be used in engineering where high mechanical characteristics, excellent behavior with friction and wear. Their chemical compositions are given in Table 2.

Table 2: The chemical compositions of experimental specimens

Material: 20MnCr5 - Chemical composition, Mass (%)							
C	Mn	Cr	Si	Ni	Cu	Nb	S
0.22	1.23	1.11	0.29	0.08	0.06	0.03	0.025
P	Ti	W	Mo	V	Al	Rest	-
0.021	0.02	0.02	0.01	0.01	0.01	96.864	-
Material: CuSn7Pb6Zn6 - Chemical composition, Mass (%)							
Cu	Zn	Sn	Pb				
83.23	5.08	7.06	4.63				

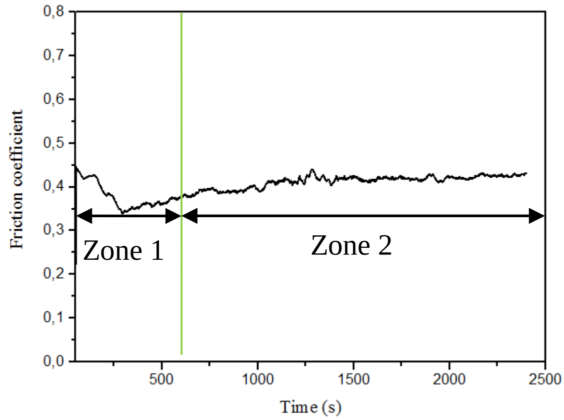
Results and discussion

Influence of time on the evolution of the friction coefficient

Figure 3 shows the variation of the friction coefficient versus time for applied load and electrical current. In these curves, we can easily identify two distinct zones:

- The first, it is a transient phase (unsteady phase) which lasts about 5 minutes and in which the friction coefficient μ varies between two extreme values: μ_{min} and μ_{max}.
- The second, which characterizes the steady state and the equilibrium stage is characterized by stability of the operating conditions at the interface.

However, the tribological behavior does not only depend on the couple of the materials [13], but also on the films present at the interface. In fact, the first moments of friction or unsteady phase are difficult to reproduce from one test to another, because of the sensitivity to small changes in the geometry or surface preparation.



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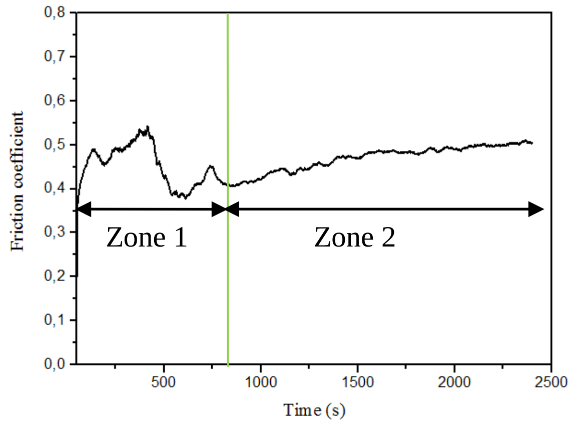


(b)

Figure 3: Evolution of friction coefficient with time, P = 18 N, V = 2.3 m/s, (a) I = 0 A, (b) I = 3 A.

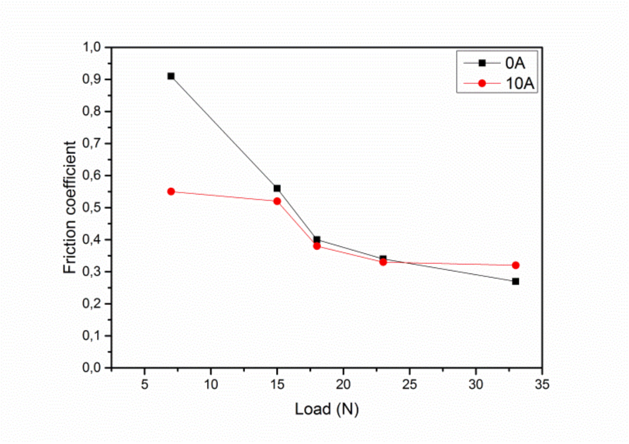
At the beginning of each test, fluctuations occur due to the transfer of the bronze to the steel cylinder. After this transitional period, operating conditions at the interface become stable [14, 15]; friction coefficient stabilized, surface roughness, depth of layers deformed, composition and microstructure of the surface layers (the steady state). The transfer mechanism increases on the disc and acts as a lubricant to facilitate the sliding between the two surfaces (antagonists).

Effect of normal load on the friction and the wear

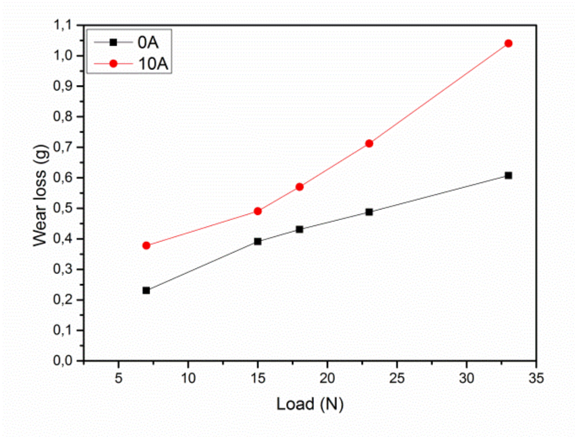
Figure 4(a) shows the variation of the friction coefficient with normal load with and without electrical current. Without electrical current, the examination of this figure shows that the friction coefficient decreases rapidly between 7 N and 18 N and shows a moderate decreasing to the load 33 N and tends to stabilize itself. With an electrical current, the friction coefficient subsequently decreased slightly when the applied load increased.

It is found that the increasing of the normal load generates a significant reduction in the friction coefficient [16, 17]. This is mainly due to the transfer mechanism of the pin to the surface of the disc. Initially, the normal load P is not strong enough to produce significant friction, or, its increasing imposes a pressure on the contact surface which produces a considerable friction coefficient. In fact, in small normal loads, the surfaces cling by nesting the asperities of antagonists, it is also increasing the adhesion of the couple surfaces. Conversely, when the normal load increases, the tangential force also increases and the plastic deformation becomes important, the heat generated by the mechanical and electrical friction and the contact temperature increases the oxidation of surfaces, and the generating of an oxide film acting as a lubricant [17]. In addition, it is found that most of the wear particles consist of metal, and in certain values of applied load the friction coefficient remains constant whatever this value. This corresponds to an increasing in the real contact surface [18, 19]. In addition, the detachment of the bronze particles and their transfer on the surface of the disc facilitate sliding.

In the other hand, the harder particles (third body) will get in to the softer surface and cause more wear. Usually the harder particles coming from adhesive wear, where junction produced are force to break up.



(a)



(b)

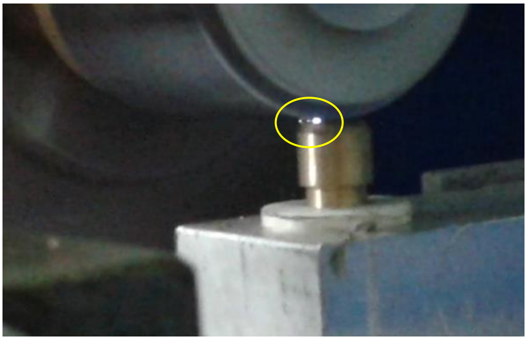
Figure 4: (a) The friction coefficient and (b) wear loss of bronze with applied loads under 0 A and 10 A of applied currents P = 18 N, V = 2.3 m/s.

Figure 4(b) shows the relationship between the wear and the normal load, with and without electrical current. As we can see the wear loss increases with and without the applied of electrical current. On the other hand, the wear loss with electrical current is more important than without it. In fact, the increase of the normal load, results an increasing of the real contact area and the transfer of bronze.

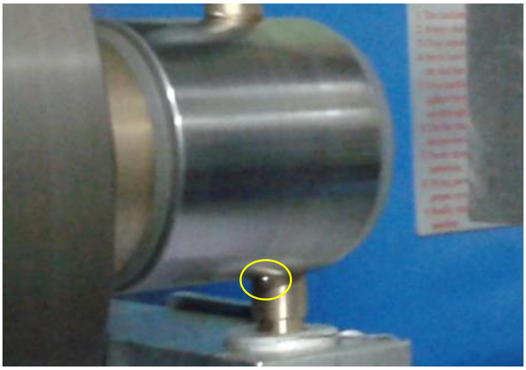
During the tests of this couple, it was observed the appearance at the interface two types of debris. Passive particles in the form of coarse grains, as soon as formed, these debris trained and evacuated out-track of friction and did not play a significant role. Active particles of finer size are interposed at the interface and contribute to the abrasion wear process. They are presented in the form of powder consisting of a mixture of metal and oxides (black debris), to which other interfacial components are added. They remain in the interface and accelerate the removal of metal (bronze) [13, 18].

It was reported that mechanical wear increased with the increase of the applied load [5].According to Holm [20], wear with electrical current included mechanical wear, electrical wear, and spark wear. The total wear can be expressed by the sum of all them.

The phenomenal arc discharge (Figure 5) appears to form craters and ablation of metal. In fact, this phenomenal has a direct effect on the contact between the disc and pin samples, which increase the wear of pin samples. In the other hand, it was reported that the appearance of arc discharge in contact leads to a change in the nature of the oxide [18].



(a)



(b)

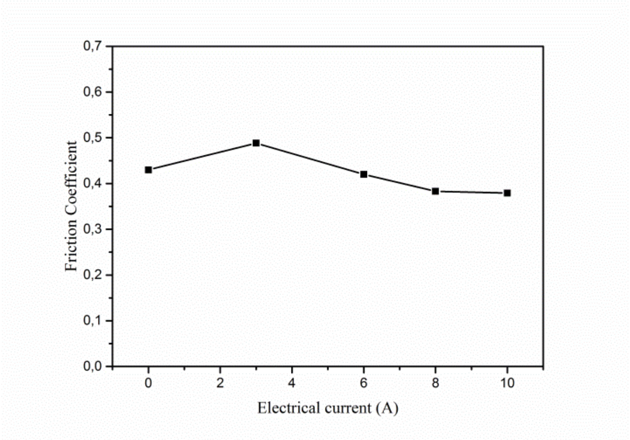
Figure 5: Arc discharge V = 2.3 m/s (a) 6 A, (b) 10 A.

Effect of the electrical current on the friction and the wear

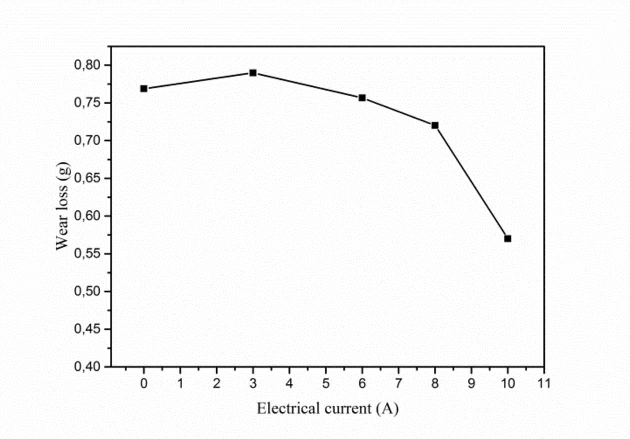
Figure 6(a) represents the relationship between the friction coefficient and electrical current, as we can see the friction coefficient decreases when the electrical current increases.

The friction coefficient fluctuates as the sliding time increases. After an initial transient period (about 600 to 750 s), the friction coefficient reached steady-state. This trend existed under all test conditions. The steady state or the equilibrium stage was attributed to the formation of film covering the contact surface of 20MnCr5 steel.

An oxide layer formed on the contact surface due to a temperature increase (the heat generated by friction) and the Joule effect at the frictional interface.



(a)



(b)

Figure 6: (a) The friction coefficient and (b) wear loss of bronze under different intensities of electrical current and applied loads. V = 2.3 m/s, P = 18 N.

It is found that the main role of the electrical current is similar to a film lubricant. In fact, the electrical current generates a raise in the temperature at the interface contact (Table. 3). Accordingly, the oxides formation is facilitated. Holm [20] found that the passage of electrical current through two metals in relative movement leads to increase the surface temperature of contact, which reduces the energy of the bonds between the antagonists in contact. Consequently, the sliding is facilitated.

Table 3: The temperature of pin specimens under different electrical currents and applied loads

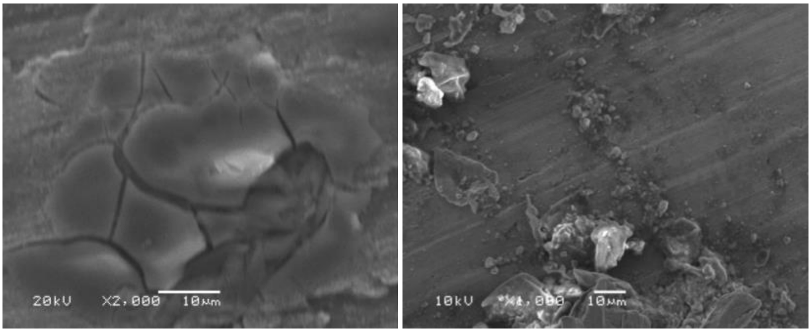
Current(A)	Temperature(°C)	
Load(N)	0	10
7	59	82
15	60,5	85
18	61,5	111
23	64	121
33	73	155

In fact, it was reported that the high temperature accelerates the oxidation phenomenon [21, 22]. According to Bouchoucha [23], the friction coefficient is affected by the mechanical properties of the formed oxide films on the sliding surfaces.

Figure 6(b) shows the relationship between the wear losses of bronze with the application of the electrical current. The wear loss initially decreased slowly as the electrical current increased from 0 A to 8 A, this is explained by the fact that the low intensity of electrical current has a negligible effect on wear loss. On the value of 10A, we can see that the wear loose is more important. This behavior is probably due to the formation of oxides which are grown in the form of a thin layer. Moreover, these oxides lead to a reduction in the real surface of contact of the couple, and thus of adhesion and wear. In fact, it was reported that wear is not influenced so much by the electric current, except in the case of strong intensities where the phenomenon of oxidation is activated [13].

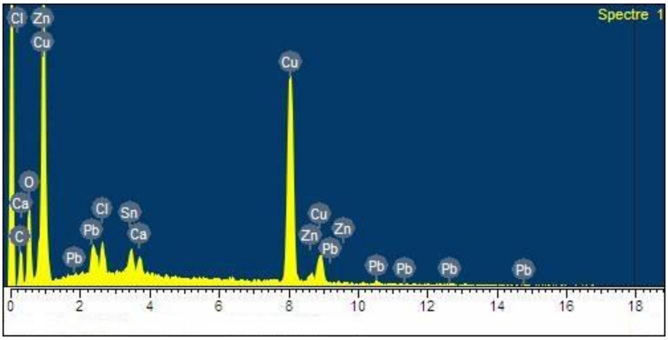
Observations of worn surfaces

Figures 7 and 8 present SEM and EDX spectra of the worn surfaces of pin on bronze. From these figures, we can observe the presence of oxygen element peak wich confirms that an oxidizing reaction was occurred, in addition to several elements. In fact, this is due to a mutual transfer between the antagonist surfaces identified by EDX.

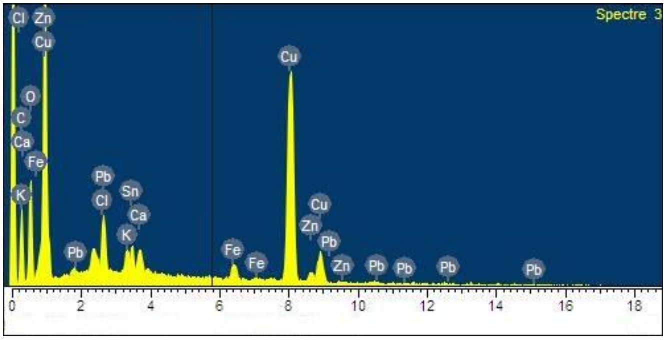


(a) (b)

Figure 7: SEM micrographs of worn surfaces of bronze pin v = 2.3 m/s, P = 18 N (a) 3 A (b) 10 A.



(a)



(b)

Figure 8: EDX spectra of bronze worn surface V = 2.3 m/s, P = 18N (a) 3 A (b) 10 A.

In Figures 9 and 10, the formation of transfer films on worn surfaces of 20MnCr5 steel is shown using an Altisurf profelometer and optical microscope. It is clear that an adhesion was occurred. It was reported that adhesion at metal-to-metal junctions and shear stiffness in the film junctions serve to create resistance to sliding (friction) and cause metal transfer [24].

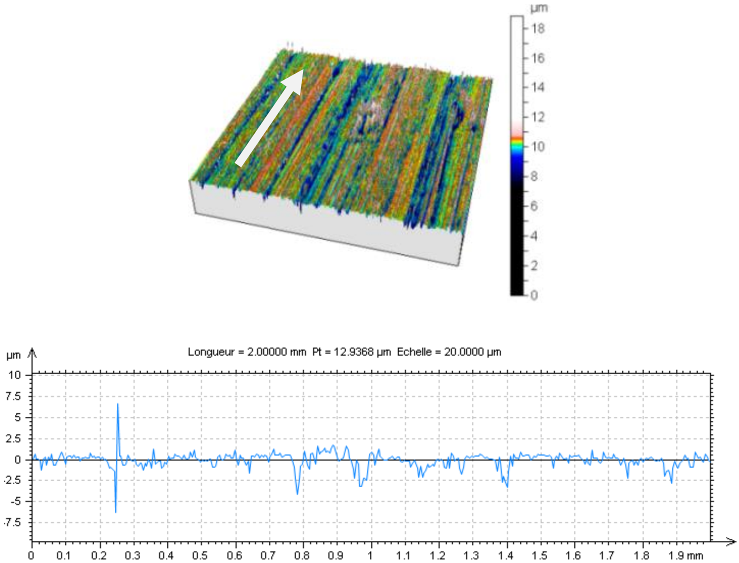
Figure 11 (a)-(b) are the optical microscope morphologies of the pin samples during the dry sliding wear tests with and without electrical current. As we can observe there were many grooves on the worn surface of the pin sample, which were attributed to scratching from abrasive wear. During tests, it was also observed that the transferred film covered the worn surface of the disc sample, and the transferred film coverage of the surface increased with a high applied load and sliding speed without and with electrical current. The evolution of the final apparent contact area provides abrasion scratches in the direction of the slide which is more visible when the load and electrical current increases.

The damaged surfaces of the pin are analyzed by Profilometer for each test (Figure 12). The three-dimensional surface topographies of the wear tracks formed show that the abrasion scratches are very clear. Wear tracks are characterized by surface deformation in form of smooth longitudinal grooves running parallel to the sliding direction. This is explained by previous results showing the increased wear of bronze.

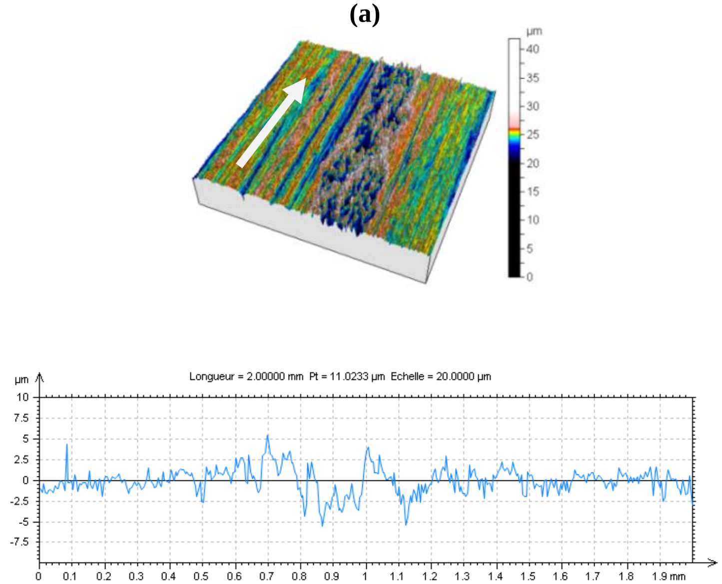
The roughness arithmetic mean R_a of the profile of the wear tracks are shown in the table 4. It is seen that an increase of applied electrical current leads to an increase in the roughness arithmetic mean R_a. This behavior is explained by the sever plastic deformation during testes by the crossing of electrical current.

Table 4: Roughness arithmetic average R_a of bronze specimens under different electrical currents

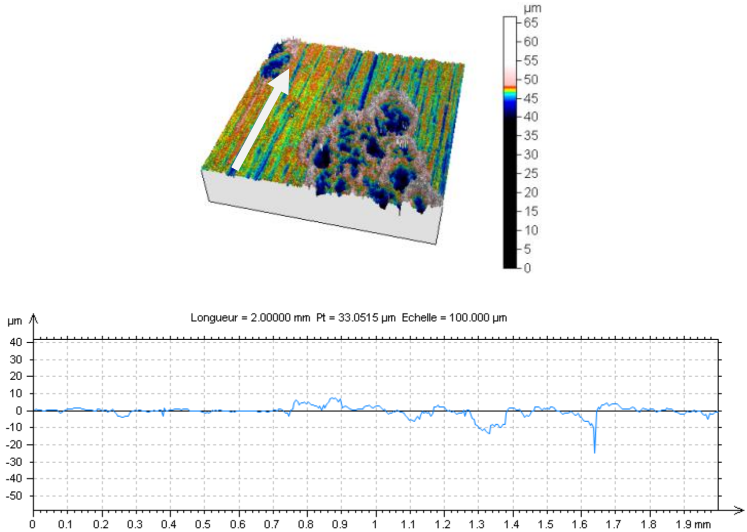
Current(A)	R_a (µm)
0	0,88
3	0,94
6	1,22
8	2,01
10	3,35


µm
18
16
14
12
10
8
6
4
2
0
Longueur = 2.00000 mm Pt = 12.9368 µm Echelle = 20.0000 µm
µm
10
7.5
5
2.5
0
-2.5
-5
-7.5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 mm

(a)


µm
40
35
30
25
20
15
10
5
0
Longueur = 2.00000 mm Pt = 11.0233 µm Echelle = 20.0000 µm
µm
10
7.5
5
2.5
0
-2.5
-5
-7.5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 mm

(b)



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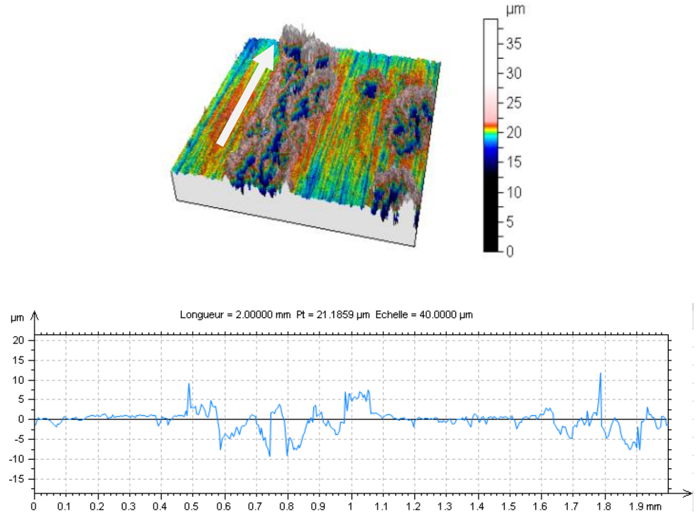
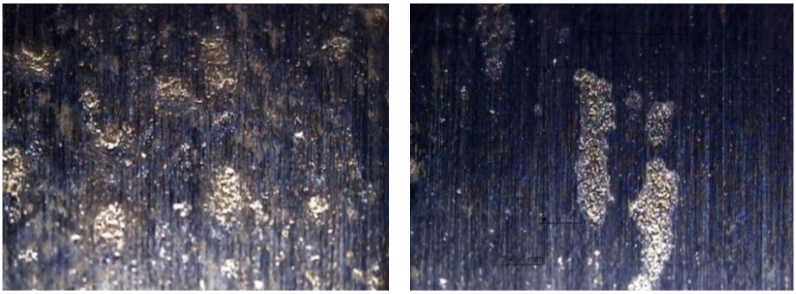


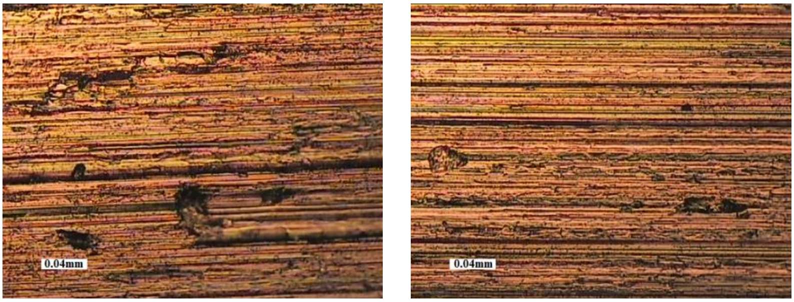
(d)

Figure 9: 3D surface topographies of transfer films formed on 20MnCr5 steel for different electrical currents (a) 0 A (b) 3 A, (c) 6 A, (d) 10 A.



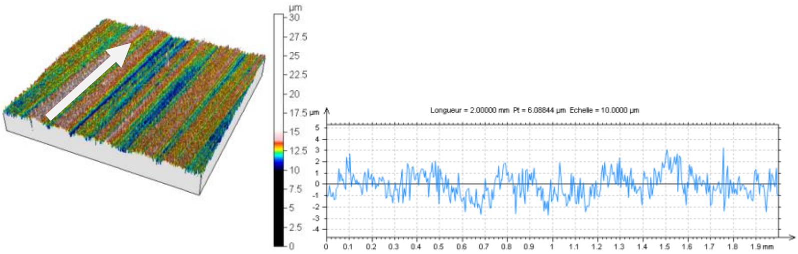
(a) (b)

Figure 10: Optical microscope morphologies of the disc samples V=2.3 m/s P=18 N, (a) 8 A, (b) 0 A.

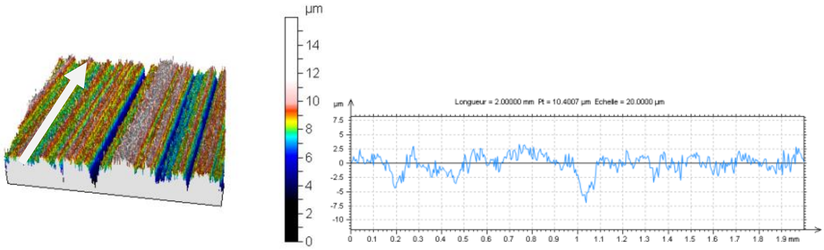


(a) (b)

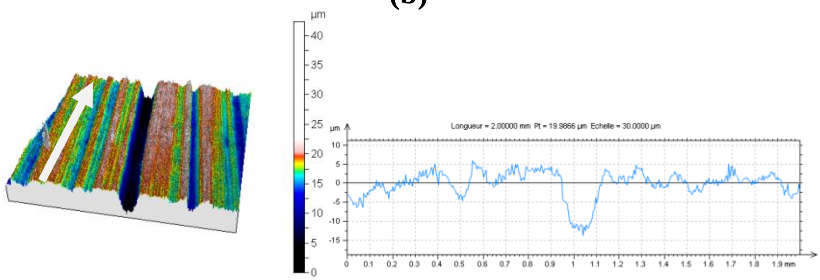
Figure 11: Optical microscope morphologies of the pin samples (X40) V = 2.3 m/s P = 18 N, (a) 6 A, (b) 0A.



(a)



(b)



(c)

Figure 12: 3D surface topographies of worn surfaces of bronze (a) 0 A, (b) 6 A, (c) 10 A.

Wear mechanisms

The wear is the main cause of failures in most of machines in the industrial sector. It is dependent on wear mechanisms arising during friction. In the literature, it was reported that the wear mechanisms under mechanical and electrical parameters including adhesion, abrasion, arc erosion and plastic deformation [18,25-26]. These mechanisms have been re-examined in the present tests. The principal wear mechanisms observed in our tests are adhesion, abrasion, oxidation, arc erosion and plastic deformation. In high loads and sliding speed of 2.3 ms^{-1} with electrical current, the electrical arc ablation and severe plastic deformation are the most dominant wear mechanisms. In fact, the friction and the wear are significantly affected by interfacial films, but unlike the friction, wear is a sensitive process and can vary from one factor to two or more, for small changes in the experimental conditions. Indeed, for high speed and loads, the transfer mechanism of the bronze to the disc increases. This transfer leads to the formation of the layers on the surfaces of the disc and affect the tribological behavior of the couple.

Conclusion

A series of tests have been performed to understand the friction and wear behavior of CuSn7 bronze rubbing against 20MnCr5 steel under some mechanical and electrical parameters. The following conclusions can be concluded:

- The normal load and applied electrical current play a major role in the friction and wear behavior of the couple studied.
- The wear loss decreased with the increase of the electrical current (from 0.78 to 0.56 g). On the other hand, the wear loss increased with the increase in the applied load and especially with an applied electrical current (from 0.56 to 1.01 g).
- The formation of the active particles accelerates the removal of the bronze and governs the tribological behavior of the couple.
- Bronze transfer on the disc surface and oxides formation had a significant effect on the friction and wear of the couple studied, and their role similar to that of a solid lubricant.
- Adhesion, abrasive wear, arc erosion and plastic deformation were the main wear mechanisms of the couple studied.

Acknowledgment

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