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EVALUATION AND CHARACTERISTICS OF FRICTIONAL DISSIPATED ENERGY OF BRASS AND BRONZE IN SLIDING SYSTEM

S. Senhadji [1,2] **R. Yahiaoui** [1,2]

1. Department of Electromechanical Maintenance, Institute of Maintenance and Industrial Safety, University of Oran 2 Mohamed Ben Ahmed, Oran, Algeria, salima.senhadji@gmail.com, reda.yahiaoui@univ-oran2.dz
2. Laboratory of Production Engineering and Industrial Maintenance, University of Oran 2 Mohamed Ben Ahmed, Oran, Algeria

Abstract- Copper alloys are considered as an effective solution to reduce the severity of wear that is responsible of material loss and surface damage. Consequently, the service life of machine parts can be significantly reduced, making it essential to understand and to characterize the tribological behavior of these materials. The dissipated energy approach has emerged as an effective method for assessing the evolution of wear in various materials and to compare their wear resistance even under different environmental conditions. In this study, the frictional behavior and dissipated energy of brass and bronze were investigated through rubbing tests using a pin-on-disc apparatus, while considering the effects of applied pressure and disc roughness. The results show that bronze exhibits a negligible wear compared to brass, and that the surface roughness of the disc is the predominant factor affecting the evolution of the coefficient of friction. Additionally, the use of energy approach reveals that the wear volume loss can be linearly correlated to the dissipated energy during rubbing. This linearity is characterized by two wear coefficients whose values seem to be affected by the surface disc roughness.

Keywords: Friction, Wear, Brass, Bronze, Roughness, Frictional Dissipated Energy.

1. INTRODUCTION

Wear is a frequently encountered issue that can lead to various problems in industrial applications, including increased maintenance expenses, reduced equipment efficiency, and safety hazards. According to Liu, et al. [1], wear and frictional energy dissipation contribute to significant economic losses, accounting for around 2-7% of the gross domestic product annually. Copper alloys are often considered as a favorable choice in this regard, and they are widely used in numerous industrial sectors, particularly when high wear resistance is required under specific lubrication conditions, such as in rolling element bearings, gears, clutches, synchro meshes, and electrical components [2-4]. The investigation of the tribological behavior of these alloys continues to garner interest despite significant efforts already made in this field. It was found that the coefficient of friction (COF) variation of brass (UZ 40 M3A) during running-in conditions in a lubricated environment is more appropriately characterized by a normalized hydrodynamic parameter [5]. Additionally, the analysis of the tribological characteristics of $CuZn_{39}Pb_3$ alloy in vacuum conditions demonstrates its high suitability for use as a sliding component [6]. On the other hand, friction tests conducted on leaded-tin bronzes that contain a solid lubricating phase have shown that the presence of the lubricating phase does not consistently enhance wear resistance [7]. Additionally, the examination of wear performance of the material of mono-block rolling plain bearing under different lubricating oil conditions, revealed that the environmental parameter, specifically the concentration of solid particles, has the most significant impact, leading to increased volume loss and friction coefficient [8].

The wear process is affected by a variety of factors, including those determined by working conditions (e.g., normal load, sliding velocity, viscosity, temperature), those related to the materials in contact (e.g., microstructure, texture, Young's modulus, and stacking fault energy), and those concerning surface microgeometry [9-14]. Hsu, et al. [15] conducted an exhaustive literature review and identified 32 parameters that have been used by several researchers to describe their experimental data. Among all these parameters, which are considered to have a significant influence on wear behavior, particular attention has been devoted to the roughness of the contacting surfaces, the sliding velocity and the applied load [16-18].

Many models have been announced to describe the frictional behavior and wear characteristics of materials, with several laws being proposed. One of the earliest and most well-known models is Archard's law, correlates wear volume with the applied load and sliding distance [19]. Although it is simple and widely used, Archard's law is most effective in dry or boundary lubrication regimes, as mentioned by Lijesh, et al. [20]. However, it does not account for all parameters involved in the wear process nor their variability during rubbing [21, 22].

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An alternative approach to the Archard wear model is based on the frictional dissipated energy of the rubbing surfaces, which considers the interfacial shear work and establishes a correlation between the dissipated energy and the volume loss [23, 24]. This approach has been used to evaluate wear evolution in a variety of materials and wear mechanisms, as well as to compare their susceptibility to wear at different environmental conditions. Myslinski, et al. [25] have recently used the energy approach to model wear in thermo-elasto-plastic rolling contact problems. Similarly, Argatov, et al. [26] utilized this approach to study the evolution of fretting wear in the gross-slip regime. Additionally, Wandel, et al. [27] conducted an analysis using the energy approach to identify the predominant wear mechanisms and assess their effects on the functioning of oscillating bearings. The current work aims to establish a comparative analysis of the wear characteristics of two copper alloys by examining the variation of the COF and the frictional dissipated energy during sliding. A series of experimental tests is performed to carry out this analysis, which specifically focuses on the influence of surface roughness and applied pressure on the wear behavior of these materials.

2. EXPERIMENTAL CONDITIONS

Tribological tests were performed on a pin-on-disc tribometer to characterize the wear and friction of brass and bronze pins rubbing against an XC42 steel disc under lubricated conditions (Figure 1). A 100 Neutral Solvent (100 NS) lubricant was used and maintained at 25 °C throughout the experiments. Cylindrical brass and bronze pins, with chemical compositions provided in Table 1 and measuring 5 mm in diameter and 12.5 mm in length, were used against a cylindrical counter body with inner and outer diameters of 25 mm and 64 mm, respectively.

All experiments were conducted at a fixed sliding velocity of 0.5 m/s and were replicated twice using a new pin for each test, which allowed for the calculation of the average of COF values. Frictional force measurements were continuously acquired via a coupled load sensor integrated into the tribometer. The detailed experimental conditions are summarized in Table 2.

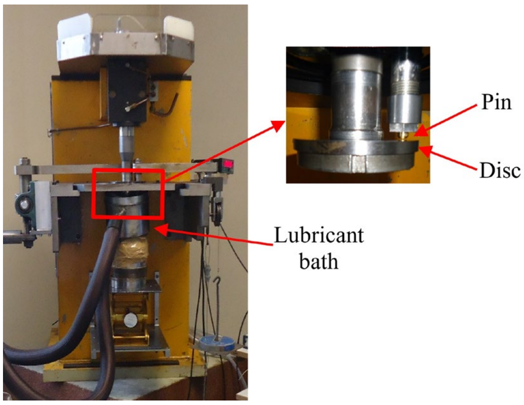


Figure 1. General view of the pin-on-disc tribometer (Supmeca-Paris)

Table 1. Chemical composition of pins

Materials	Chemical composition [%]				
	Cu	Zn	Pb	Sn	P
Brass	57.72	39.34	2.94	-	-
Bronze	91.24	-	-	8.29	0.47

Table 2. Summary of tests conditions

Test Parameters	Values	
Nominal Pressure (MPa)	1 and 10	
Pin Material	Brass ($CuZn_{39}Pb_2$)	Bronze ($CuSn_9P$)
Micro Hardness (Hv)	170	190
Initial pin Roughness *Ra* (μm)	0.44	0.19
Disc Material	XC_{42} (250 Hv)	
Disc Roughness *Ra* (μm)	0.15 and 2	
Lubricant	Neutral 100 (η= 0.034 Pa.s)	

3. RESULTS AND DISCUSSION

The performed experimental tests provided the COF evolution of brass and bronze with respect to the sliding distance (Figure 2). The obtained results reveal that the COF of bronze is primarily influenced by the disc roughness, and it can be observed that it is drastically reduced when the disc with low surface roughness is used. In contrast, the effect of disc roughness on the COF of brass appears to be significant only for low-pressure conditions ($P = 1$ MPa).

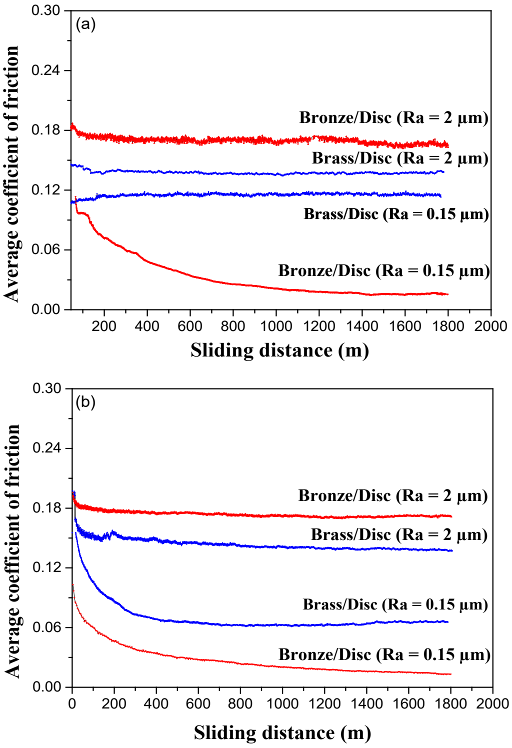


Figure 2. Variation of the COF with sliding distance for pressure of: a) 10 MPa, b) 1 MPa

Volume loss measurements were conducted after each test to characterize the wear of the studied materials. The results indicate that bronze experiences no significant wear, as evidenced by the very low volume loss (Table 3) and the imperceptible wear track observed on the disc surface (Figure 3a). In contrast, brass exhibits more pronounced wear, with significant volume loss and clear wear track on the disc surface (Figure 3b).

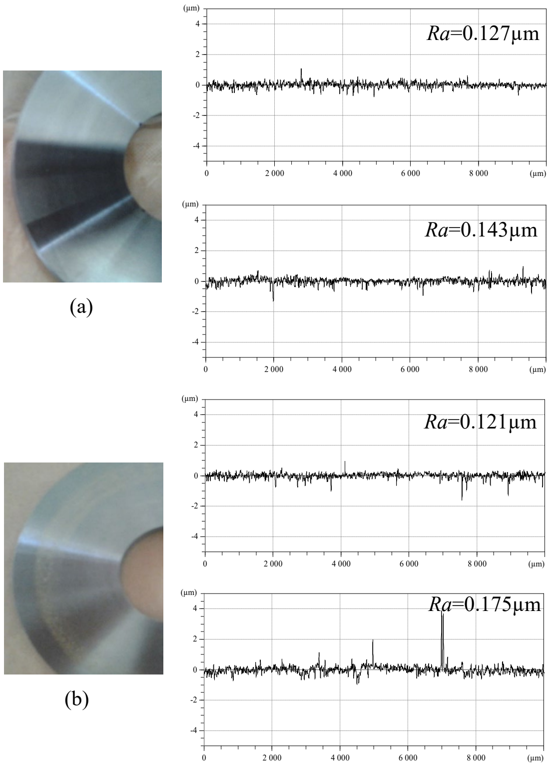


Figure 3. Wear track and roughness measurements of surface disc rubbed against, a) bronze, b) brass

Table 3. Volume loss (ΔV) of the pins

Pressure (MPa)	Disc roughness *Ra* (µm)	Volume loss (cm^3)	
		Brass	Bronze
1	0.15	6.21×10^{-4}	9.09×10^{-5}
	2	4.96×10^{-3}	3.64×10^{-4}
10	0.15	1.47×10^{-2}	1.59×10^{-4}
	2	2.49×10^{-2}	8.30×10^{-4}

An energetic approach is used to analyze the wear behavior of brass and bronze. The underlying assumption is that the energy expended by the tangential force is equivalent to the energy dissipated during the relative motion of the contacting surfaces. Consequently, the dissipated energy (E_d) can be expressed as follows [21]:

$$dE_d = F_t\left(x\right)dx = F_n.\mu\left(x\right)dx \tag{1}$$

$$E_d = F_n\int_0^x \mu\left(x\right)dx \tag{2}$$

where, dE_d is the increment in the dissipated energy, dx is the incremental displacement, μ is the COF and F_n is the normal load. Numerical integration is used to evaluate the area under the COF-sliding distance curve, corresponding to the integral in Equation 2. The evolution of the E_d of the two materials with the sliding distance is represented in Figure 4. The results indicate that the E_d is significantly affected by pressure, except for bronze when rubbed against the smooth disc, where this effect is relatively reduced.

Although the E_d appears to vary linearly with the sliding distance, the running-in phase could potentially affect this linearity since the tangential force has not yet reached a stable state. During the running-in phase, the surfaces in contact undergo a process of adaptation, resulting in the smoothing of asperities and an increase in the real contact area. This phase can lead to variations in the tangential force, which can affect the apparent linearity of the E_d with respect to the sliding distance, as observed in the case of bronze rubbed against the smooth disc. Consequently, it is more appropriate to describe the variation of E_d using a power law function of the form:

$$E_d = a\,x^b \tag{3}$$

The values of a and b are given, in case of bronze, in Table 4.

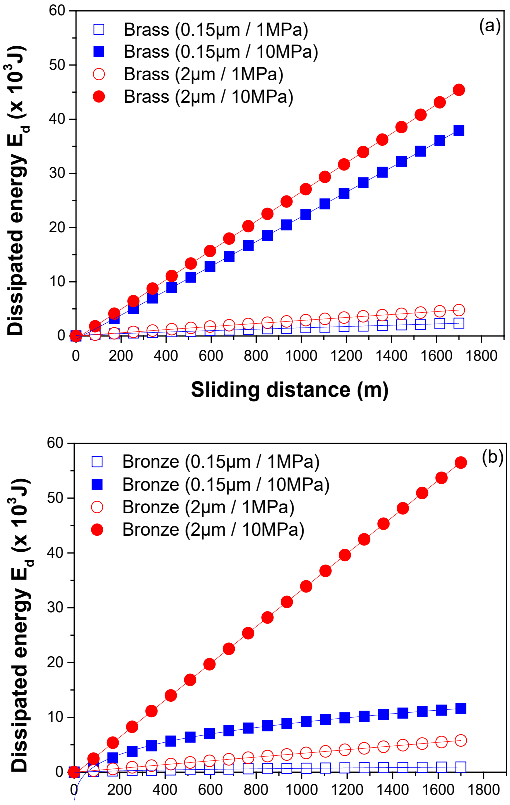


Figure 4. Variation of dissipated energy with sliding distance, a) brass, b) bronze

Table 4. Values of coefficients *a* and *b*

Disc roughness *Ra* (µm)	Pressure (MPa)	*a*	*b*
0.15	1	10.19	0.61
	10	181.92	0.56
2	1	3.75	0.99
	10	31.33	1

The exponent b in Equation (3) indicates the extent of non-linearity between the dissipated energy and sliding distance. This exponent is especially valuable in the case of the smooth disc. Special attention was given to examining the effect of the roughness of disc on the wear of brass at high pressure, where significant wear was observed. It is established that the dissipated energy and wear volume are linearly related, as shown in Figure 5.

This correlation is characterized by a threshold energy E_{dth} and an energy coefficient wear α. The coefficient α represents the slope of the linear fit and can be used as a measure of wear resistance [28]. On the other hand, the linear fit does not cross the origin, indicating that there is no wear below a certain dissipated energy threshold E_{dth} [29, 30].

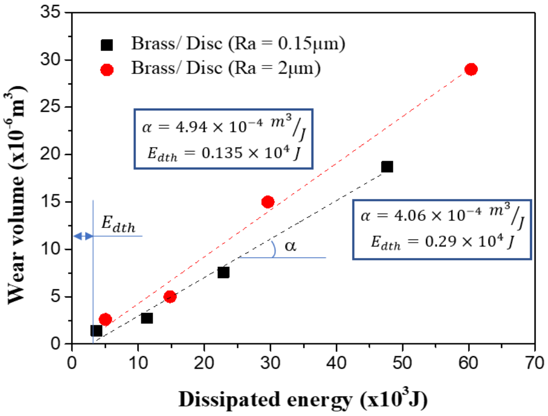


Figure 5. Variation of wear volume with the dissipated energy

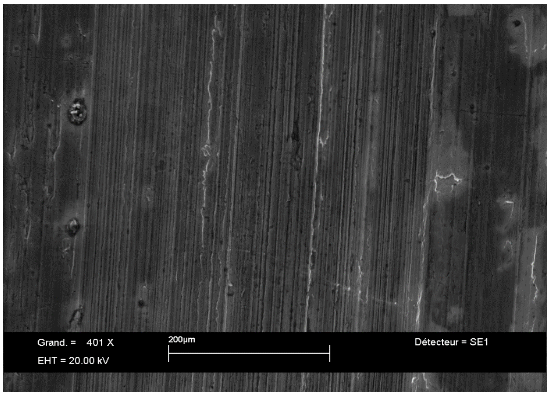
It is worth noting that the values of α and E_{dth} are affected by the disc roughness, as observed in Figure 5. The rubbing tests conducted with the rough disc resulted in a higher slope α value, indicating a more severe wear for the same energy delivered to the tribological system. This effect can be attributed to the fact that the lubricant film's capacity to sustain the load is significantly affected by the surface roughness [31, 32]. Higher surface disc roughness leads to an increase in the normal load carried by asperities, which is responsible of the high plastic deformation of the worn surface, as evidenced by the extensive deeper grooves formed in the sliding direction (Figure 6a).

In contrast, only a few shallow grooves were observed in the case of the smooth disc (Figure 6b). Considering that the developed plastic deformation is a determinant factor in the cracking process and material removal [33], more pronounced wear is expected in the case of the rough disc. On the other hand, the rough disc leads to a slightly reduced dissipated energy threshold for wear initiation. This reduction is associated with the increased number of asperities in contact that are not fully covered by the lubricant film, making them more susceptible to undergoing severe microdamage and thereby promoting wear initiation.

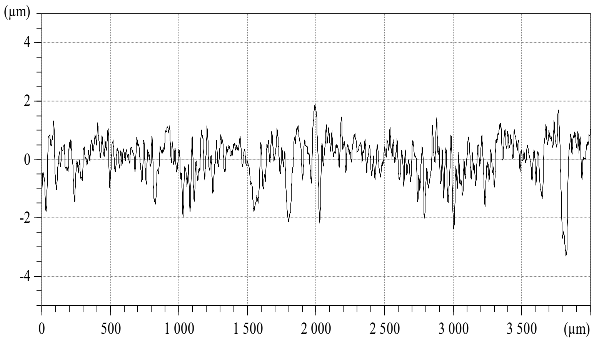
6. CONCLUSIONS

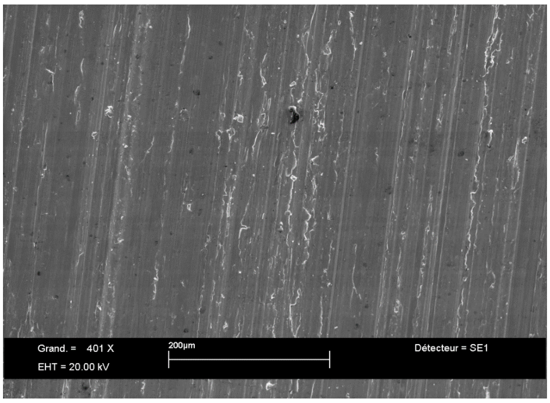
The present work aimed to characterize the tribological behavior of brass ($CuZn_{39}Pb_2$) and bronze ($CuSn_9P$) using rubbing tests on a pin-on-disc apparatus. By analyzing the evolution of the COF and the frictional dissipated energy during sliding, the following conclusions can be drawn:

- The friction coefficient of bronze, which experiences no significant wear, is primarily governed by the surface disc roughness. Whereas in the case of brass, it is affected not only by the surface disc roughness but also more significantly by the applied pressure.



(a) R_a=0.480µm





(b) R_a=0.791µm

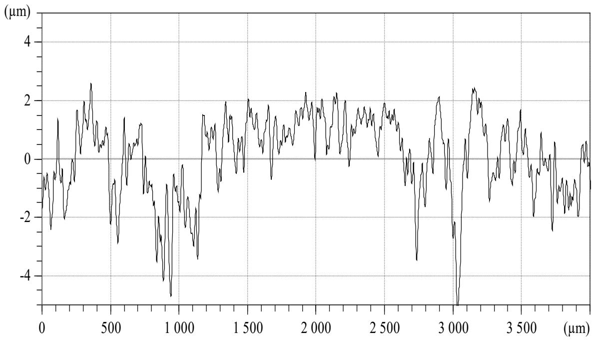


Figure 6. SEM micrographs and roughness profile of the worn surfaces of brass pin (P = 10 MPa), a) brass/smooth disc (Ra = 0.15µm), b) brass/rough disc (Ra = 2µm)

- While the dissipated energy seems to vary linearly with the sliding distance, this correlation may exhibit non-linear characteristics, as observed in the case of bronze rubbed against a smooth disc, owing to the influence of the running-in phase.

- A power law function characterizes more effectively the relationship between the dissipated energy and the sliding distance, as it considers the effect of the running-in phase on the evolution of the dissipated energy.
- The dissipated energy and wear volume are linearly related and characterized by a threshold energy (E_{dth}) and an energy wear coefficient (α), whose values are affected by the surface roughness of disc and the applied pressure.
- The use of rough disc leads to a reduced dissipated energy threshold for wear initiation. This reduction is associated with the increased number of asperities in contact that are not fully covered by the lubricant film, making them more susceptible to undergoing severe plastic deformation and thereby promoting wear initiation.

NOMENCLATURES

1. Acronyms

COF	Coefficient of friction

2. Symbols / Parameters

E_d : Dissipated frictional energy, J

E_{dth} : The energy threshold, J

dE_d : The increment in the dissipated energy

dx : The incremental displacement

F_t : Sliding friction force, N

F_n : The applied normal load, N

α : The energy wear coefficient, mm^3/J

μ : Friction coefficient

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BIOGRAPHIES

Name: **Salima**
Surname: **Senhadji**
Birthday: 07.12.1973
Birthplace: Oran, Algeria
Bachelor: Graduate Degree in Physics, Department of Physics, Faculty of Physics, University of Oran, Oran, Algeria, 1996
Master: Materials Science / Electrical and Optical Impedance of Semiconductors, Application to Oxides, Department of Physics, Faculty of Physics, University of Oran, Oran, Algeria, 2001
Doctorate: Tribology / Experimental Study of Friction and Wear Behavior in Plane Contact of Brass and Bronze in a Lubricated Environment, Department of Physics, Faculty of Physics, University of Sciences and Technology Mohamed Boudiaf of Oran, Oran, Algeria, 2018
The Last Scientific Position: Assist. Prof., Department of Electromechanical Maintenance, Institute of Maintenance and Industrial Safety, University of Oran 2 Mohamed Ben Ahmed, Oran, Algeria, Since 2018
Research Interests: Physics, Tribology, Material Science
Scientific Publications: 11 Papers, 3 Projects, 1 Theses

Name: **Reda**
Surname: **Yahiaoui**
Birthday: 27.12.1973
Birthplace: Oran, Algeria
Bachelor: Department of Mechanical Engineering, University of Sciences and Technology Mohamed Boudiaf of Oran, Oran, Algeria, 1995
Master: Mechanics and Physics of Materials / Numerical Modeling of Fatigue Damage, Department of Physics, Faculty of Physics, University of Sciences and Technology Mohamed Boudiaf of Oran, Oran, Algeria, 2002
Doctorate: Physics / Materials Science / Study of Short Fatigue Crack Growth: Quantitative Characterization and Modeling, Department of Physics, Faculty of Physics, University of Sciences and Technology Mohamed Boudiaf of Oran, Oran, Algeria, 2013
The Last Scientific Position: Assoc. Prof, Department of Electromechanical Maintenance, Institute of Maintenance and Industrial Safety, University of Oran 2 Mohamed Ben Ahmed, Oran, Algeria, Since 2021
Research Interests: Fatigue Damage, Fracture Mechanics, Reliability
Scientific Publications: 15 Papers, 5 Projects, 2 Theses