Influence of Dry Friction on the Wear Behavior of X52 Steel -Experimental Study and Simulation Using Response Surfaces Method

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Abstract

The objective of this work is to identify the most influential parameters on the friction coefficient and wear rate, using the response surface method. The friction tests were carried out by adopting the methodology of complete planes 2^3 at three factors ("D", "V" et "Py"), at two level for each factor. The results show a decrease in the wear rate when the three factors are at their highest level and a decrease in the friction coefficient when using minimum loads and speeds on important distances. In addition, the developed mathematical models make it possible to reveal a correlation between the test parameters and the responses studied in their studied domain. An evaluation of the volume parameters "Vmc" and "Vvv" was carried out. The morphology of the worn surface shows that the friction under a load of 1 N leads to the predominance of an abrasive wear mechanism, while a load of 10 N favors an adhesive wear mechanism, increasing the parameters "Vmc" and "Vvv" to the maximum.

1. Introduction

The surface is the most important part of any engineering component [1]. In service, the surfaces of mechanical systems are subjected to severe conditions, they are the most exposed to external attacks such as wear, corrosion and fatigue, which reduces their service life [2] and compromises the operation. Therefore, interface phenomena play a crucial role in engineering, and their evaluation and their control contribute to the development of many advanced domain such as electronics, information technologies, energy, optics and tribology [3, 4]. To improve the performance and the surfaces lifetime of mechanical parts, several techniques, among which, heat treatments which are applied to mechanical parts to strengthen their wear resistance, corrosion and fatigue. These treatments enhance the mechanical properties of steels, such as the elasticity limit, tensile strength and hardness as well as tribological characteristics [5, 6]. Friction is a very important parameter, which provides information on the materials behavior in contact. In addition, it governs many variables such as the contact stresses and its conditions as well as the formation of transfer film/debris. Friction coefficient (COF) and the formation of transfer film/debris are subject to several factors during sliding contact, among which, the surface topography is one of the most influential factors [7]. Surface topography reflects the characterization of surface wear, fatigue and corrosion behavior of materials [8–10]. Surface roughness constitutes one of topography elements, which allow to characterize the materials degradation subjected to different tribological conditions (friction, lubrication and wear) [11–14]. The evaluation methods based on response surface models (RSM) as well as numerical simulations used to predict the surfaces behavior of materials during mechanical contact. This work aims to study the evolution of the volumetric parameters (Vmc and Vvv) after friction test as well as the prediction of friction coefficient and the wear rate by mathematical models established by the complete factorial designs 2^3 according to parameters, in this case the normal load "Py", the linear speed "V" and the traveled distance "D". The experiment is carried out on a material steel X52, treated by quenching and tempering. Surface examinations by scanning electronic microscope (SEM) and a 3D profilometer were carried out in order to assess the frictional behaviour and the wear resistance of steel.

2. Materials And Methods

2.1. Material

The used material in this study is steel X52 in the treated state (quenched at 920 ° C and tempered at 740 ° C) obtained from a pipeline used in the petroleum industry. The chemical composition was made by spectrophotometric analysis on a "SPECTRO Rp 212" machine at URASM, El-Hadjar complex in Annaba, the result of this analysis is shown in Table 1.

Table 1. Chemical composition of steel X52

The elements content%													
C	S	Al	Si	P	V	Cr	Mn	Ni	Cu	Mo	Nb	Sn	Ti
0,15	0,007	0,025	0,26	0,005	0,001	0,014	1,33	0,012	0,035	0,008	0,008	0,003	0,003

The hardness test, impact test and tensile test were performed to check the material mechanical properties. The tensile test was carried out according to API 5L norm using a universal traction machine "Zwick-Roell". The mechanical properties obtained are as follows: $R_m = 549.4 \text{ MPa}$, $R_e = 395 \text{ MPa}$, $E = 155 \text{ GPa}$ and $A = 32.48\%$. The absorbed energy during the impact test is equivalent to $W = 8.8 \text{ J}$ and the average hardness is equivalent to 207.1 Hv.

2.2. Experimental methodology

It is proposed to perform friction tests on a HLE-X52 steel through plans for experiments planning "complete factorial designs 2^3 " according to the principle indicated in the diagram of Figure 1.

Three factors were considered, namely the traveled distance "D" coded (X1), the linear speed "V" coded (X2) and the load "Py" coded (X3), each one taken at 2 levels (see Table 2).

Table 2. Coded factors for tribological test

Factors	Parameters	Levels	
		-1	+1
X1	D (m)	10	50
X2	V (cm/s)	2	5
X3	Py (N)	1	10

2.3. Friction test

The friction tests were carried out at ambient temperature accordance with ASTM G99-95 norm, using a Ball-Pin/Disc tribometer from CSM-Instrument. The principle test consists of the application of a perpendicular load through a steel ball 100C6 of diameter ϕ 6mm as presented in Figure 2. Accordance with factorial plans 2^3 , eight (08) samples were cut and their surfaces polished with SiC abrasive paper of different grain sizes ranging from 400 to 1200. The tests are carried out according to the experiment matrix indicated in Table 3. The friction coefficient was recorded in real time by data acquisition using Tribox 4.49 software.

Table 3.Experiments Matrix

Test order	Input parameters			Output parameters
	Traveled distance D (m)	Linear speed V (cm/s)	Applied load Py (N)	Friction coefficient "f"
E1	10	2	1	0,612
E2	50	2	1	0,293
E3	10	5	1	0,638
E4	50	5	1	0,710
E5	10	2	10	0,441
E6	50	2	10	0,507
E7	10	5	10	0,362
E8	50	5	10	0,335

The wear volume was estimated by measuring the surface profile of the wear track. The wear rate was calculated according to the wear law proposed by Archard according to equation (1) [19].

$$W_s = \frac{V}{P \cdot D} \quad (1)$$

Where:

V (mm³) is the wear volume,

P (N) is the applied load,

D (m) is the traveled distance

The volume parameters (Vmc, Vvv) were measured using a 3D profilometer with a laser source type: Cyber Technology CT100, according to DIN ISO 25178 norm. The measurement results of the wear rate and the measured roughness parameters are shown in Table 4.

Table 4.Values of Ws, Vmc and Vvv

Test N°	Ws X10 ⁻⁵ (mm ³ /N/m)	Vmc (µm ³ /µm ²)	Vvv (µm ³ /µm ²)
E1	11,5	0,22	0,03
E2	2,701	0,41	0,07
E3	6,268	0,28	0,04
E4	4,527	0,35	0,03
E5	6,455	1,45	0,14
E6	1,963	1,26	0,08
E7	2,765	1,03	0,23
E8	0,012	0.82	0.15

The morphology of the worn surfaces and the wear mechanisms were established by Quanta 250/FEI scanning electron microscopy.

3. Results And Discussion

3.1. Evolution of the friction coefficient

Generally, friction depends on the structural properties and mechanical characteristics of material. The analysis of the curves presented in Figs. 3a, b, indicate the evolution of the friction coefficient for the tribological couple X52/100C6 according to the traveled distance. According to these curves, there are three phases (I, II and III) of friction and wear [23]. Friction begins with a lapping period during which the friction coefficient increases rapidly to reach a maximum value. This period is characterized by significant wear and plastic deformation of the surface roughness. The second phase is transition, which is characterized by a slight decrease in the friction coefficient; this is due to the formation of the third body, which under the effect of friction wear on the track plays a similar role to that of a solid lubricant. In the third phase, we observe the stabilization of the friction coefficient where the value is maintained constant whatever the traveled distance. The results of the friction coefficient recorded a minimum value of 0.293 and a maximum value of 0.71 for test N°2 and test N°4 respectively (see Table 3).

3.2 Regression analysis

The digital processing according to the complete factorial plans (2^3) allowed the elaboration of mathematical models for each of the responses ("f", "Ws") according to three considered parameters (P_y , V , D). These mathematical models offer the ability to predict the studied responses in the study domain. The friction coefficient "f" and the wear rate "Ws" are respectively expressed by equations (2) and (3).

$$f = 0.7705 - 0.01646D - 0.02451V - 0.03088P_y + 0.003706D * V + 0.001966D * P_y + 0.000593V * P_y - 0.000448D * V * P_y$$

2

$$Ws \times 10^{-5} (\text{mm}^3/\text{N}/\text{m}) = 19.26 - 0.3594D - 2.439V - 0.8929P_y + 0.06374D * V + 0.02181D * P_y + 0.1064V * P_y - 0.004925D * V * P_y$$

3

Statistical analysis shows that the residuals of the friction coefficient "f" and the wear rate "Ws" follow a straight line (Figure.4a-4b) where there is no evidence of non-normality or d'asymmetry. The residual distribution curve (Figure.4c-4d) shows that these residuals are distributed randomly around zero and without any particular trend; hence the established model explains perfectly the obtained results.

The difference between the measured and predicted responses for the friction coefficient "f" and the wear rate "W" is shown in Figures 5 (a-b). These indicate that the mathematical models obtained for the two studied responses can represent the experimental study domain. The comparison demonstrates that the predicted values of different studied responses are closer to those observed experimentally.

3.3 Surfaces of 3D response and contours

The interaction between the parameters (D , V and P_y) is highlighted by the 3D plots (figures.6-7), of responses "f" and "Ws", measured and predicted by the model (equations 2 and 3). Figures 6 (a, b and c), show that the effect of traveled distance on the friction coefficient is less significant compared to the effect of speed and load. The increase in speed leads to an increase in the coefficient "f", on the other hand, the increase in the load leads to its decrease; this is due to the iron oxide layer, which serves as protection by preventing the direct contact of two rubbing systems [22]. It can be concluded that the speed is the most influential parameter on the friction coefficient. Indeed, its increase generates a significant amount of wear debris (third body), which causes the formation of a transfer layer in the contact area. The periodic and localized rupture of this transfer layer, thus causing the increase of COF [20, 21].

Figure 7 shows the evolution of wear rate according to the parameters (D , V and P_y). From the interaction curves (Figure 7 a, b and c), we observe, on the first hand that the wear rate decreases with the increase of P_y and D , and on the other hand that the effect speed is less important. A high speed associated with a high load causes an increase of the temperature in the contact zone by modifying the reactivity of the contact surfaces towards the environment, resulting in the reconstitution of a permanent oxide film during the wear process [23].

The contour graphs are shown in Figures 8 and 9; they describe the response surfaces and allow establishing the response values ("f" and "Ws") and the corresponding parameters (D , V and P_y).

The average effects (figure.10a), showing the impact of each of parameters (D , V and P_y) on the friction coefficient, show a load predominance " P_y " tending to reduce the friction coefficient which converges towards a value less than 0.42 for $P_y = 10\text{N}$. These graphs reveal that there seems to be a big difference in the effects magnitude where the applied load is the most significant versus the speed and traveled distance. However, the average effects of each of these parameters on the wear rate (figure.10b) indicate that the traveled distance " D " followed by the applied load " P_y " being the most significant versus the speed.

Concerning the interaction between the different parameters (D , V and P_y) and their influences on the friction coefficient "f" (Figure.11a), the curves particularly show two interactions (traveled distance/speed) and (speed/load). Moreover, Figure 11b shows that only the speed interaction and the traveled distance on the wear rate "Ws" is the most significant.

3.4 Evolution of volume parameters after friction test

- Volume of core material " V_{mc} "

Currently, the volume core material "V_{mc}" is an important functional parameter in tribology, it allows to determine the quantity of lost material through wear during a work cycle [24]. Thus, more this parameter increases, more the surface better resists in fatigue, thus increasing its lifespan. The histogram in figure 12 shows the evolution of the volume of core material "V_{mc}" during the friction tests. The results reveal that the "V_{mc}" parameter reaches a maximum value of 1.45 (μm³/μm²) for an applied load P_y = 10N combined at a speed V = 2cm/s and a distance D = 10m (test E5). The minimum value of "V_{mc}" which is equivalent to 0.22 (μm³/μm²) was recorded during test E1 using a load P_y = 1N, at a speed V = 2cm/s over a distance D = 10m. So, we can see the significant effect of the load whatever the speed and the traveled distance; indeed the "V_{mc}" parameter tends to increase considerably for a maximum load of 10N.

This can be explained by the fact that a high load favors a larger contact surface and a more regular flow of material, hence a lesser removal of debris, which is in agreement with Bourebia et al [25]. This debris is crushed under the load effect and adheres to the contact surface that allowing the reinforcement of "V_{mc}".

• Volume of the valleys void "V_{vv}"

The volume of the valleys void "V_{vv}" is an essential element in lubrication, it plays an important role in lubricant retention, and it reduces friction and preserves the state of the contact surfaces [16]. The results illustrated in figure 13, show that the applied load is the most dominant factor which affects the parameter "V_{vv}" where a strong load P_y = 10N generates an increase in "V_{vv}" reaching a maximum of 0.23 (μm³/μm²) for a speed V = 5cm/s. This is explained by the fact that an important load ensures a better penetration of the rubbing body in the contact zone, which has the effect of generating pockets serving as lubricant retention, which is shown by F. Blateyron [24]. However, the applications of a low load P_y = 1N generates wear debris that is pushed back into the valleys and encrusted in the contact zone causing a decrease in the voids volume.

3.5 Morphology of wear tracks

The SEM micrographs taken from the worn surfaces for test E1 and test E8 show the highest and lowest wear rates, respectively (see figure 14).

The micrograph of the test "E1" reveals the parallel grooves to the sliding direction, confirming the predominance of abrasive wear favoring the delamination of the rubbed surface. This degradation of the surface is produced by the detachment of asperities generated by plastic deformation and hardening [26]. In addition, the micrograph of the test "E8", shows the existence of detached flakes from the contact surface, it is a sign of the appearance of adhesive wear. This explains that during sliding, the contact asperity undergoes plastic deformation which accumulates during repeated contact [27]. Hence the predominant wear mechanism is adhesive wear, which is more intense for the 10N load [28]. This can be linked to the structural state and to the adhesion of iron oxide to the contact surface forming the third body. In addition, the good ductility of these iron oxides makes non-abrasive particles favorite the wear by adhesion [26].

4. Conclusion

From the obtained experimental results in this work, the ball friction tests on the surfaces of steel X52 under loads, at different speeds and traveled distances, allowed to determine the most significant parameters on the friction coefficient and the wear rate. The methodology of complete factorial plans (2³) has allowed us to quantify the friction coefficient "f" and the wear rate "W_s" according to parameters (D, V and P_y). The following conclusions can be drawn.

1. The mathematical models developed allowed to predict the friction coefficient "f" and the wear rate "W_s" according to the test parameters (D, V and P_y) in the study field.
2. The main effects and interactions curves as well as the 3D contour curves obtained by numerical simulation, permitted to elucidate the influence of parameters (D, V and P_y) on the studied responses "f" and "W_s".
3. The lowest wear rate W_s = 0.012x10⁻⁵ mm³/N/m was obtained using the following parameters: P_y = 10N, V = 5 cm/s and D = 50 m.
4. The parameters providing a minimum friction coefficient (f_{min} = 0.293) were recorded during test N ° 2 (P_y = 1N, V = 2cm/s and D = 50m).
5. The application of a maximum load at a minimum distance increases the parameters "V_{mc}" and "V_{vv}" which respectively reach their maximum 1.45 (μm³/μm²) and 0.23 (μm³/μm²) for minimum and maximum speeds.
6. The adhesive wear mechanism was observed when using a load 10 N; conversely, the use of a low load of 1N generates an abrasive wear mechanism.

Abbreviations

D	Traveled distance
V	Linear speed
Py	Normal load
Vmc	Volume of core material
Vvv	Volume of the valleys void
X1	Coded factors for D
X2	Coded factors for V
X3	Coded factors for Py
Y	Output response (for f, and Ws)
RSM	Responses surface methodology

Declarations

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Figures

Figure 1

Schema of experiments

Figure 2

Ball-Pin/Disc tribometer

Figure 3

Evolution of the friction coefficient according to the traveled distance, a) tests E1, E3, E5, E7 and b) tests E2, E4, E6, E8

Figure 4

Residual plots for "f" and "Ws"

Figure 5

Predicted and measured values of responses: a- the COF "f"; b- the wear rate "Ws"

Figure 6

Iso response curve of friction coefficient versus the load, speed and traveled distance

Figure 7

Iso response curve of wear rate versus the load, speed and traveled distance.

Figure 8

Contour graphs for friction coefficient depending on P_y , V , D .

Figure 9

Contour graphs for wear rate depending on Py, V, D.

Figure 10

Main effects plot for: a): "f", b): "Ws"

Figure 11

Interactions plot for:a): "f", b): "Ws"

Figure 12

Evolution of the volume of the core material "Vmc", after friction test

Figure 13

Evolution of volume of the valleys void "Vv" after the friction test

Figure 14

a) SEM micrographs of test 1, b) SEM micrographs of test 8