



Influence of dry friction on the wear behavior of X52 steel—experimental study and simulation using response surfaces method

Soumaya Meddah¹ · Mounira Bourebia¹ · Kaddour Gherfi¹ · Laouar Lakhdar² · Amel Oulabbas¹ · Sihem Achouri¹ · Latifa Kahloul³

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Abstract

Friction and wear phenomena alter the behavior of the material surface, where certain relevant parameters which characterize the surface are influenced. Therefore, the objective of this work is to identify the parameters most influencing the friction coefficient (f), the wear rate (Ws), and the volume parameters (V_{mc} and V_{vv}) during the friction test. The friction tests were carried out by adopting the methodology of 2^3 complete planes with three factors (D , V , and P_y), at two levels each. The results show a decrease in the wear rate when all three factors are at their highest level and a decrease in the friction coefficient when using minimum load on speed long distances. In addition, the mathematical models developed allow to reveal a correlation between the test parameters (D , V , and P_y), and the responses studied (f , Ws) in their study field. Moreover, the volume parameters V_{mc} and V_{vv} were evaluated during the tests, and 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 promotes an adhesive wear mechanism.

Keywords Complete plans · Modeling · Friction coefficient · Wear rate · Volume parameters

Nomenclature

D	Traveled distance
V	Linear speed
P_y	Normal load
V_{mc}	Volume of core material
V_{vv}	Volume of the valleys void
X_1	Coded factors for D
X_2	Coded factors for V
X_3	Coded factors for P_y
Y	Output response (for f , and Ws)
RSM	Responses surface methodology

1 Introduction

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 reduce their service life [1] and compromises the operation. Therefore, the surface is the most important part of any engineering component [2]. Friction work causes the loss of operating power after pieces surfaces wear; therefore, surface integrity is generally considered an important aim in manufacturing processes to predict the service properties and pieces lifetime [3]. Therefore, surface integrity and machined components can be greatly affected by tribological conditions [4]. To improve the performance and the surfaces lifetime of mechanical parts, several techniques, among which, are 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]. Surface topography reflects the characterization of surface wear, fatigue, and corrosion behavior of materials [7–9], since it is one of the most influential factors [10], which

✉ Soumaya Meddah
meddahsoumaya@gmail.com; s.meddah@crti.dz

¹ Research Center in Industrial Technologies, CRTI, P.O.BOX 64, 16014 Chéraga, Algeria

² Industrial Mechanics Laboratory (LMI), Badji Mokhtar University, P.O. Box.12, 23000 Annaba, Algeria

³ National Higher School of Mines and Metallurgy-Ammar Laskri, P.O. Box.32, 23000 Annaba, Algeria

allow to characterize the materials degradation subjected to different tribological conditions (friction, lubrication, and wear) [11–13]. Moreover, friction is a very important parameter, which provides information on the materials behavior in contact. In machining, the friction effect is an important issue, to simulate the turning operation during the machining process. Tribological phenomena at these interfaces are not fully understood. Several studies have been carried out, where scientists use two approaches [14–16]. The first approach is to use the cutting process itself and the second is to use laboratory friction tests (pin/disc friction conditions) to fully understand the wear mechanisms at tool/chip and tool/piece interfaces. On the other hand, laboratory tests make it possible to control contact conditions more precisely and to modify these conditions at will; thus, in this same context, we can cite some works:

- Ana Isabel Fernández-Abia et al. [17] have developed a model for the prediction of specific cutting force when machining austenitic stainless steels using the mechanistic approach at high cutting speeds. The results show that the specific cutting coefficients were obtained by applying the force model as an inverse model. They were validated by comparing the values estimated by the model with those obtained by experimentation.
- The same authors [18] presented a methodology for evaluating the performance of advanced tools PVD intended for turning difficult-to-machine materials. They performed on four types of coatings' (AlTiSiN (nACo®), AlCrSiN (nACRo®), AlTiN and TiAlCrN) different tests such as wear test, analysis of cutting forces, EDX analysis of inserts, and roughness pieces. The results indicate that the best coatings for turning difficult-to-machine materials like austenitic stainless steels are nACo® and AlTiN coatings, as they offer the best performance.
 - R. Polvorosa et al. [19] have presented the results of face-turning tests for two alloys common in machining, the airplane engine components Inconel 718, and Wasp alloys, in comparing Wear models of these tools at different coolant pressures at 6 (conventional) and 80 bar. The results show that the behaviors of the two alloys are different depending on the pressure value; moreover, these results allowed to obtain different wear models, where in the case of Wasp alloy, the wear is severe.
- J. Pereira et al. [20] have evaluated the wear and dry friction behavior at low and high temperature (25 and 500° C) of NiCoCrAlY and CoNiCrAlY laser coatings, as well as steel austenitic stainless steel AISI 304 used as a substrate against the Al₂O₃ ball. Wear test results show a reduction in the high temperature wear rate for all materials tested. For the NiCoCrAlY coatings, the high temperature reduces the friction coefficient, while it greatly increases the friction coefficient of the CoNiCrAlY coatings. The principal mode of damage is abrasion wear and adhesion wear.
- K. Lin et al. [21] have studied the effect of the point radius (0.4, 0.6, 0.8, and 1.0 mm) of the tool and the tool wear on the distribution of residual stresses during turning of TiB₂/7050 Al composites. The results show that the distribution of residual compressive stresses is always obtained on the machined surface and the subsurface (subsurface), regardless of the new or worn tools.
- T. Kagnaya et al. [14] studied the wear mechanisms of the WC–Co cutting tool under tribological conditions, where dry friction experiments are performed on a high-speed pin/disc tribometer (10 m/s) considering the WC–Co pin against AISI 1045 grade steel discs. In addition, the change in temperature as a function of the friction coefficient has been studied by modeling approaches. The results show that WC–Co tribological pions exhibit different wear mechanisms, and the friction coefficient decreases as the sliding speed and the temperature of the pion increase. Furthermore, the friction coefficient and the temperature curves always have the same evolution as a function of the test duration.
- J. Rech et al. [22] have identified a model to predict TiN-coated WC–Co cutting tool wear when machining AISI304L stainless steel using the open tribometer with a coherent range of sliding speeds and contact pressures. The results led to the identification of a new wear model implemented in a digital cutting model to locally simulate tool wear.
- J. Rech et al. [15] have identified a friction model capable of describing the coefficient of friction at the tool/chip/piece interface when dry cutting AISI1045 steel with a TiN coated carbide tool. The results showed that the friction coefficient is very dependent on the sliding speed. A new friction model has been identified based on the average local sliding speed.
- C. Bonnet et al. [16] have identified a friction model capable of describing the coefficient of friction at the tool/chip/piece interface when dry cutting an austenitic stainless steel AISI316L with a TiN-coated carbide tool. The results showed that the friction coefficient mainly depends on the sliding speed, while the pressure is of secondary importance. In addition, a new key parameter has been revealed, namely the average local sliding speed at contact. Finally, a new friction model has been identified on the basis of this local sliding speed.

This work aims to study the evolution of the friction coefficient and the wear rate after the dry friction test as well as the volume parameters (V_{mc} and V_{vv}) of HLE steel (X52) having undergone a quenching and a tempering. The response surface methodology (RSM) was used for

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 numerical simulations in order to establish a correlation between the input parameters in this case, the normal load P_y , the linear speed V , and the distance traversed D and output responses (f , W_s). The estimations based on these models allow predicting the envisaged responses (f , W_s) in the study field. In addition, surface examinations with a scanning electron microscope (SEM) and a 3D profilometer were carried out in order to evaluate the friction behavior and the steel wear resistance.

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.

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: $R_m = 549.4$ MPa, $R_e = 395$ MPa, $E = 155$ GPa, and $A = 32.48\%$. The absorbed energy during the impact test is equivalent to $W = 8.8$ 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 Fig. 1. Three factors were considered, namely the traveled distance D coded (X1), the linear speed V coded

(X2), and the load P_y coded (X3), each one taken at 2 levels (see Table 2).

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 6 mm. 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 Tribbox 4.49 software.

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 Eq. (1) [23].

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

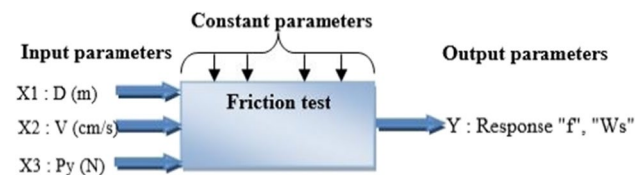
where:

Table 2 Coded factors for tribological test

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

Table 3 Experiments matrix

Test order	Input parameters			Output parameters
	Traveled distance D (m)	Linear speed V (cm/s)	Applied load P_y (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

**Fig. 1** Schema of experiments

V (mm³) is the wear volume,
 P (N) is the applied load,
 D (m) is the traveled distance.

The volume parameters (V_{mc} , V_{vv}) 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. 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. 2a, b, indicates the evolution of the friction

Table 4 Values of W_s , V_{mc} , and V_{vv}

Test N°	$W_s \times 10^{-5}$ (mm ³ /N/m)	V_{mc} (μm ³ /μm ²)	V_{vv} (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

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 [24]. 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 maintain 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 (2³) allowed the elaboration of mathematical models for each of the responses (f , W_s) 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 W_s are respectively expressed by Eqs. (2) and (3).

$$f = 0.7705 - 0.01646D - 0.02451V - 0.03088P_y + 0.003706D * V + 0.001966D * P_y + 0.000593V * P_y - 0.000448D * V * P_y \quad (2)$$

$$W_{sx}10 - 5 \left(\frac{\text{mm}^3}{\text{N} \cdot \text{m}} \right) = 19.26 - 0.3594D - 2.439V - 0.8929P_y + 0.06374D * V + 0.02181D * P_y + 0.1064V * P_y - 0.004925D * V * P_y \quad (3)$$

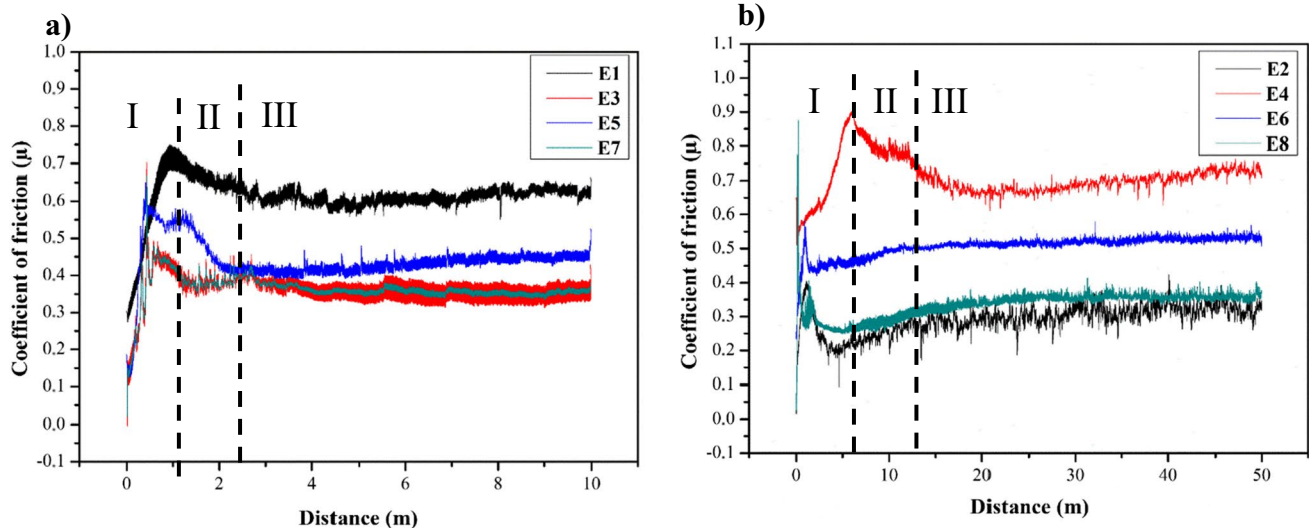


Fig. 2 Evolution of the friction coefficient according to the traveled distance. **a** Tests E1, E3, E5, E7. **b** Tests E2, E4, E6, E8

Statistical analysis shows that the residuals of the friction coefficient f and the wear rate W_s follow a straight line (Fig. 3a–3b) where there is no evidence of non-normality or d asymmetry. The residual distribution curve (Fig. 3c–3d) shows that these residuals are distributed randomly around zero and without any particular trend; hence, the established model explains perfectly the obtained results.

These mathematical models offer the possibility of predicting the responses studied in the study field. The predicted value curves for the friction coefficient f and the wear rate W_s follow the same tendency as that of the experimental values (Fig. 4 (a–b)).

3.3 3D surface response and contours

The interaction between the parameters (D , V , and P_y) is highlighted by the 3D plots (figures 5a–5b), of responses “ f ” and “ W_s ,” measured and predicted by the model (Eqs. 2 and 3). Figure 5a show that the effect of traversed 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 [25]. 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.

Figure 5b shows the evolution of wear rate according to the parameters (D , V , and P_y). From the interaction curves (Fig. 5 b), 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 the reconstitution of a permanent oxide film during the wear process [24].

The contour graphs are shown in Figs. 6 (a, b); they describe the response surfaces and allow establishing the response values (f and W_s) and the corresponding parameters (D , V , and P_y).

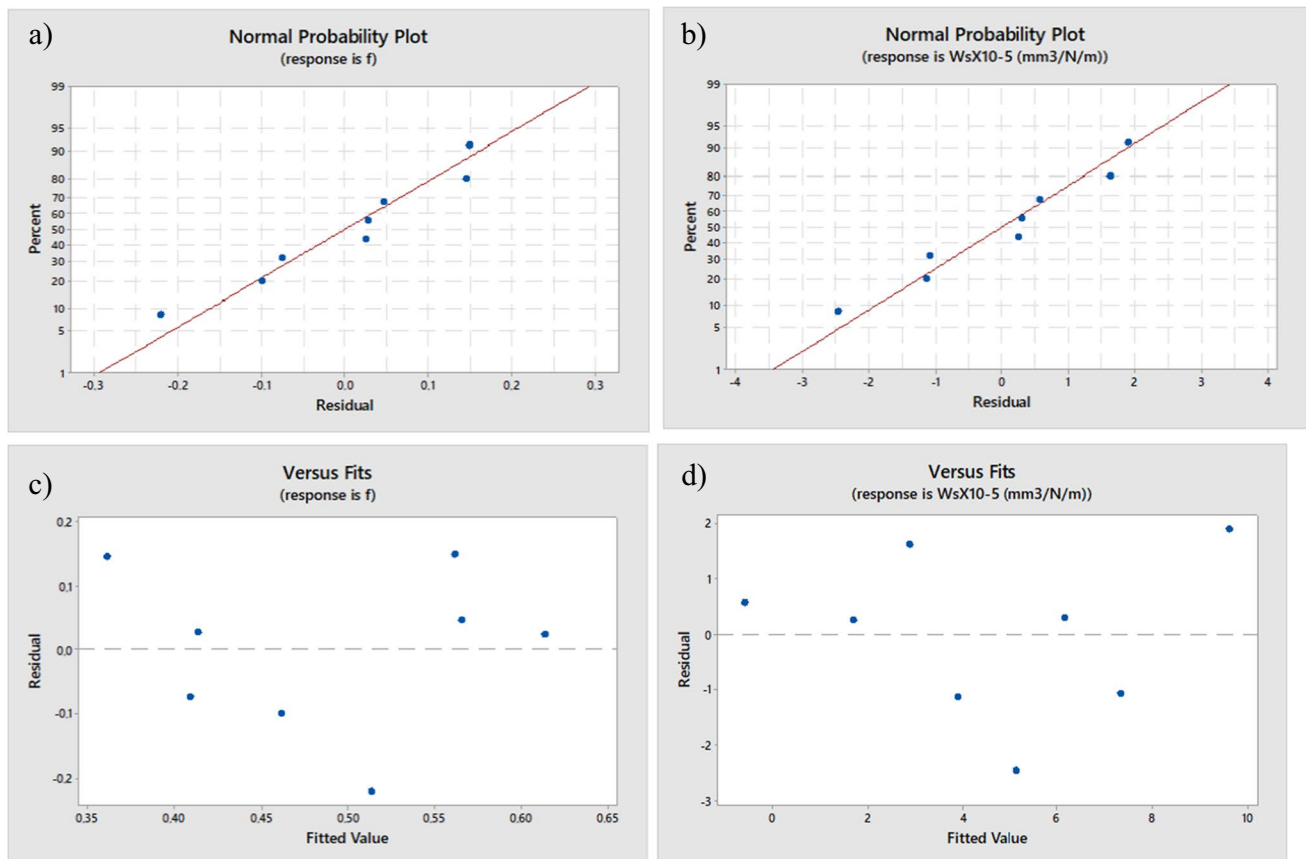


Fig. 3 Residual plots for f and W_s

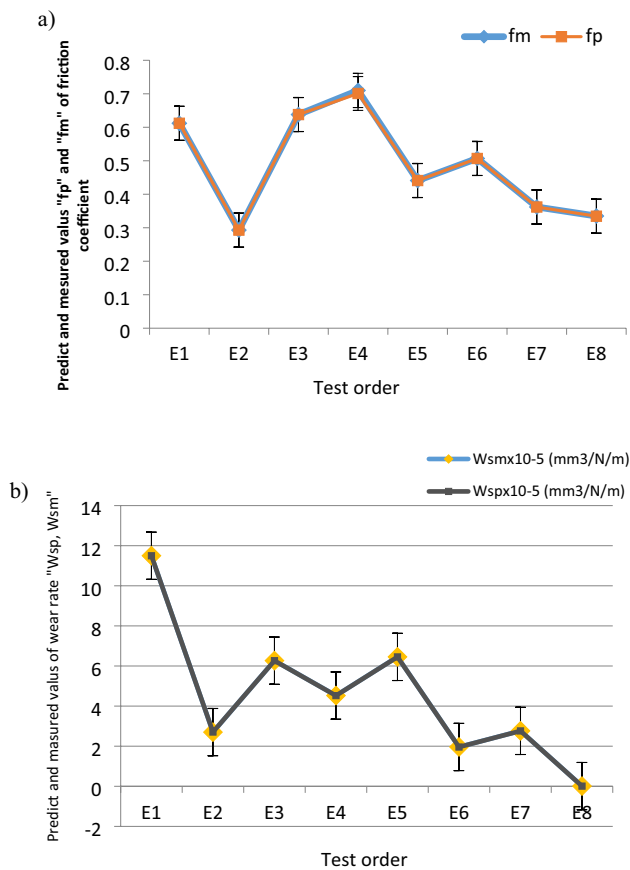


Fig. 4 Predicted and measured values of responses. **a** The COF f . **b** The wear rate W_s

3.4 Interactions effect on responses

The average effects (Fig. 7a), 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 $P_y = 10$ 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 (Fig. 7b) indicate that the traveled distance D was 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 (Fig. 8a), the curves particularly show two interactions (traveled distance/speed and speed/load). Moreover, Fig. 8b shows that only the speed interaction and the traveled distance on the wear rate W_s is the most significant.

3.5 Evolution of volume parameters after friction test

3.5.1 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 [26]. Thus, the more this parameter increases, the more the surface better resists in fatigue, thus increasing its lifespan. The histogram in Fig. 9 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 $1.45 (\mu\text{m}^3/\mu\text{m}^2)$ for an applied load $P_y = 10$ N combined at a speed $V = 2$ cm/s and a distance $D = 10$ m (test E5). The minimum value of V_{mc} which is equivalent to $0.22 (\mu\text{m}^3/\mu\text{m}^2)$ was recorded during test E1 using a load $P_y = 1$ N, at a speed $V = 2$ cm/s over a distance $D = 10$ m. 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 10 N. 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. This debris is crushed under the load effect and adheres to the contact surface that allowing the reinforcement of " V_{mc} ."

3.5.2 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 [26]. The results illustrated in Fig. 10 show that the applied load is the most dominant factor which affects the parameter V_{vv} where a strong load $P_y = 10$ N generates an increase in V_{vv} reaching a maximum of $0.23 (\mu\text{m}^3/\mu\text{m}^2)$ for a speed $V = 5$ cm/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 [27]. However, the applications of a low load $P_y = 1$ N generates wear debris that is pushed back into the valleys and encrusted in the contact zone causing a decrease in the voids volume.

3.6 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 Fig. 11). 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

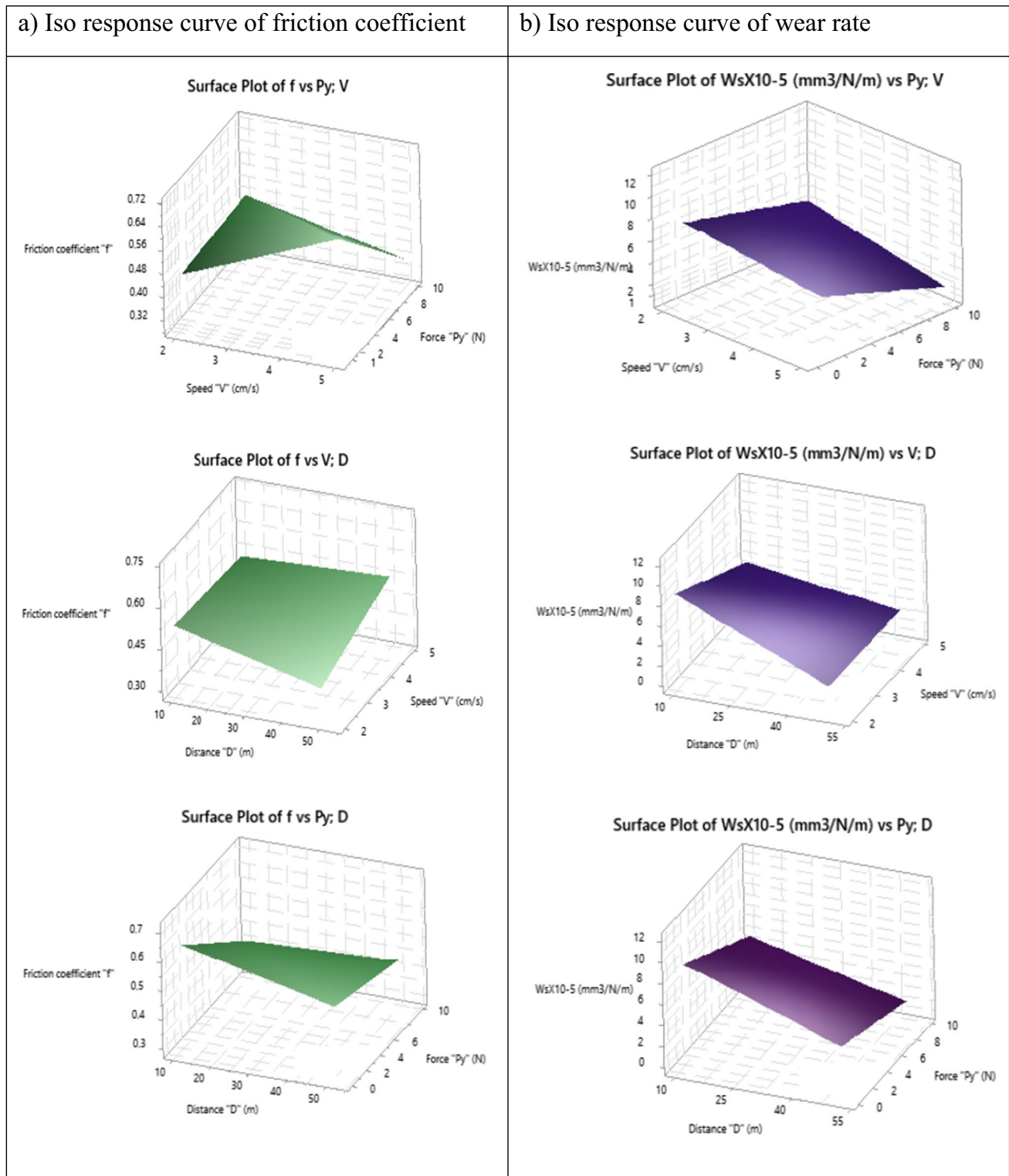


Fig. 5 Iso response curve of friction coefficient and wear rate versus the load, speed, and traversed distance

the surface is produced by the detachment of asperities generated by plastic deformation and hardening [28]. 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

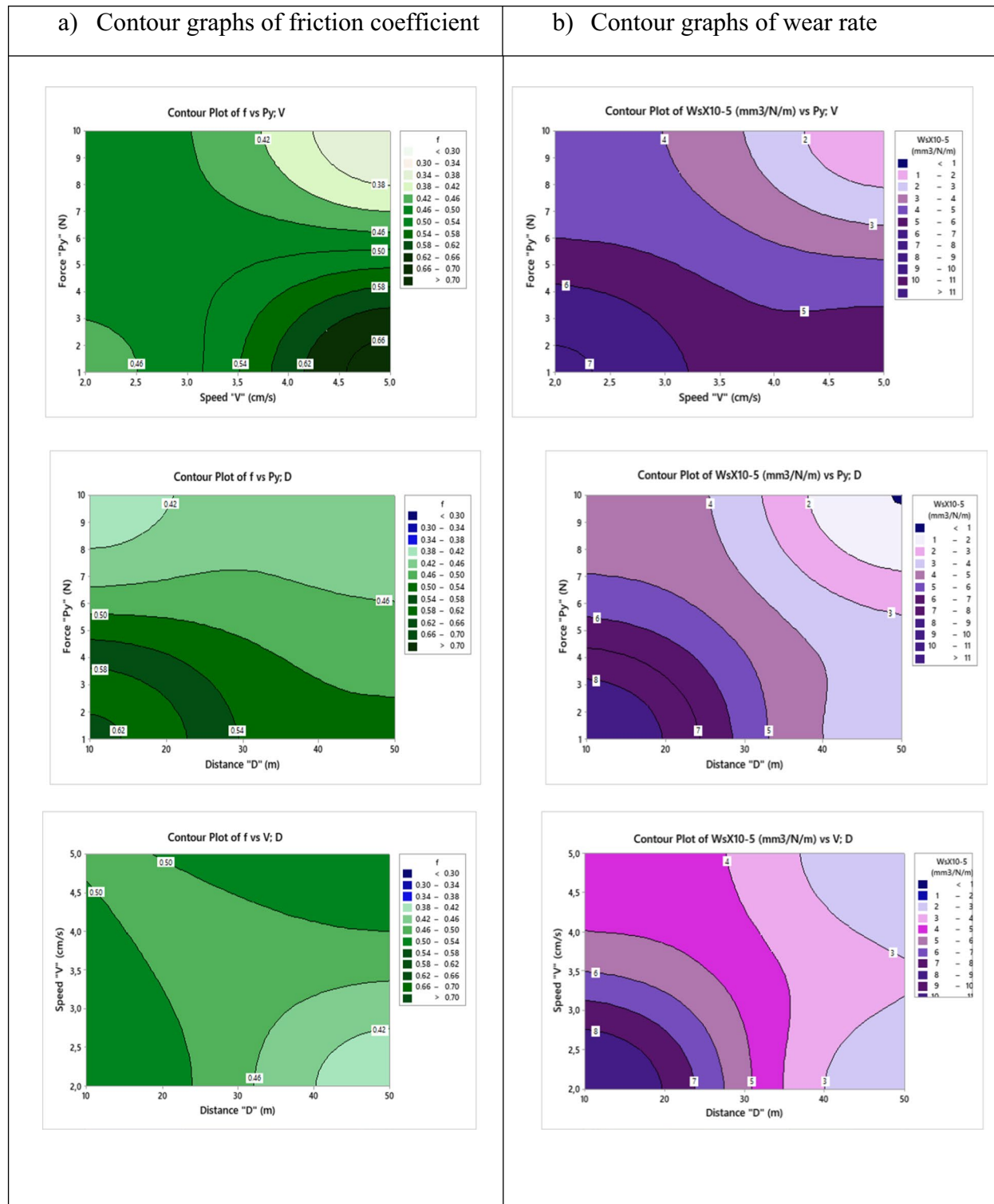


Fig. 6 Contour graphs for friction coefficient and wear rate depending on Py, V, and D

which accumulates during repeated contact [29]. Hence the predominant wear mechanism is adhesive wear, which is more intense for the 10 N load [30]. 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 [28].

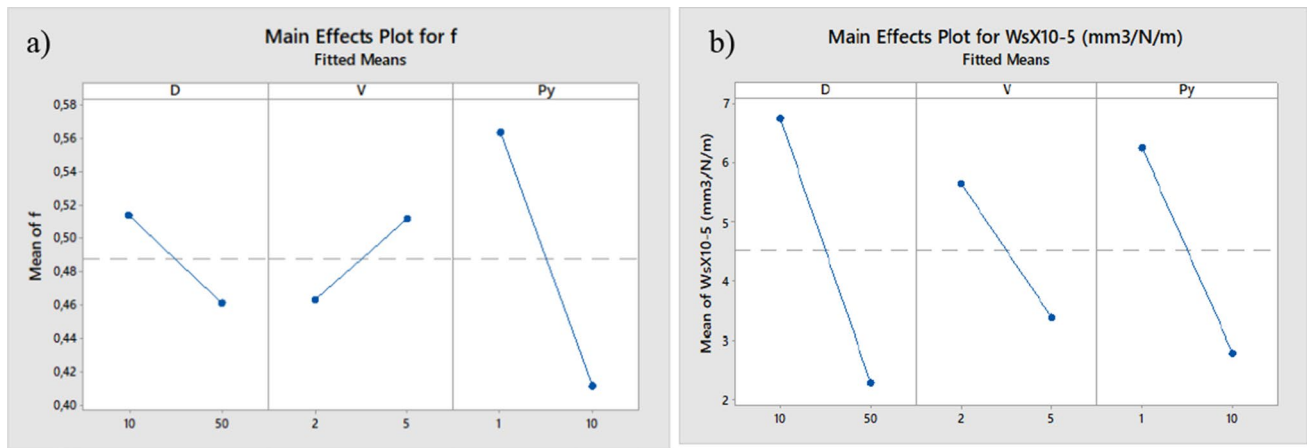


Fig. 7 Main effects plot for (a) f and (b) W_s

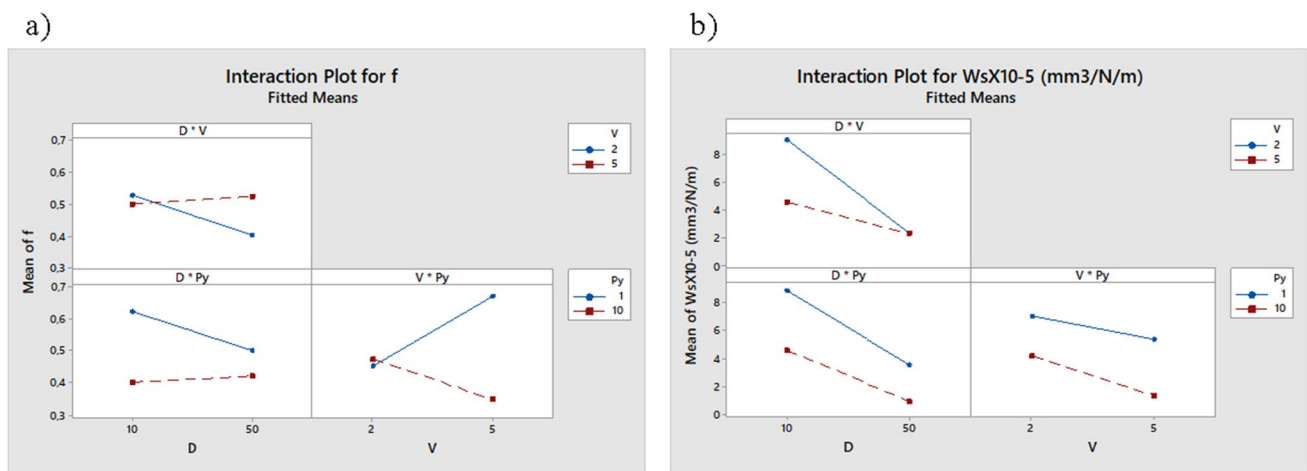


Fig. 8 Interactions plot for (a) f and (b) W_s

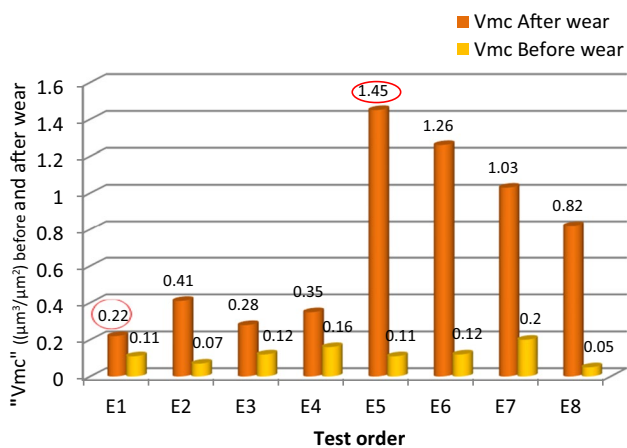


Fig. 9 Evolution of the volume of the core material “Vmc,” after friction test

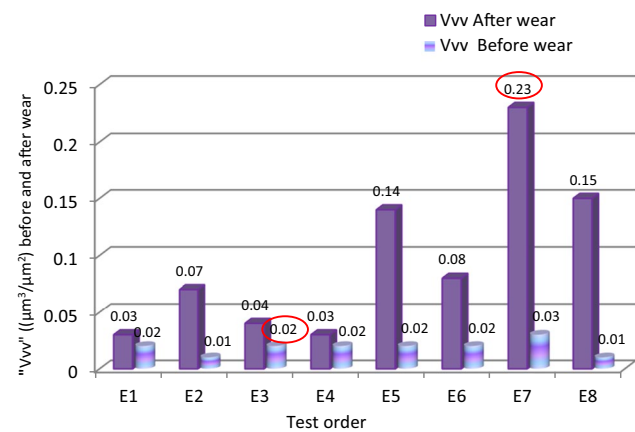
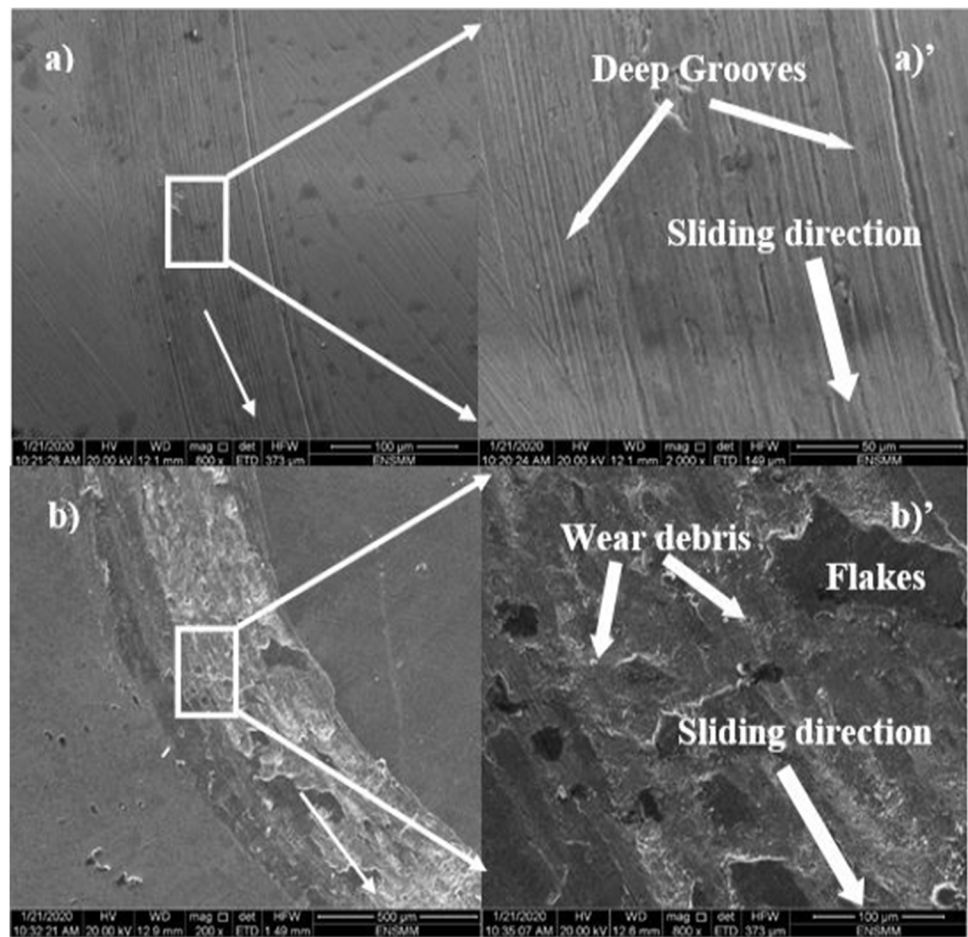


Fig. 10 Evolution of volume of the valleys void “Vvv” after the friction test

Fig. 11 **a** SEM micrographs of test 1. **b** SEM micrographs of test 8



4 Conclusion

The behavior of an HLE (X52) steel surface to friction has been studied through the monitoring of the friction coefficient, the wear rate, and the volume parameters V_{mc} and V_{vv} . The experimental results obtained in this work allowed determining the most significant test parameters affecting the responses (f , W_s , V_{mc} , and V_{vv}). In addition, the methodology of complete factorial designs (2^3) allowed the prediction of the coefficient of friction “ f ” and the wear rate “ W_s ” as a function of the test parameters (D , V , and P_y) in the domain study by means of mathematical models; hence, conclusions can be drawn.

- The iso response curves and the effects and interactions curves offer the possibility of evaluating the influence of the parameters (D , V , and P_y) on the studied responses “ f ” and “ W_s ,”
- The maximum levels of the test parameters ($P_y = 10$ N, $V = 5$ cm/s, and $D = 50$ m) reduced the wear rate to a value of $W_s = 0.012 \times 10^{-5}$ mm³/N/m. Furthermore, the friction

coefficient reaches a minimum value ($f_{min} = 0.293$) for a maximum distance (D) associated with a load and speed (P_y , V) taken at their minimum levels.

- The increase in volume parameters is favored by the application of a maximum load; where for a minimum level of speed and distance, V_{mc} reaches its maximum 1.45 ($\mu\text{m}^3/\mu\text{m}^2$) which induce better wear resistance to material. In addition, V_{vv} converges towards its maximum 0.23 ($\mu\text{m}^3/\mu\text{m}^2$) for a maximum speed associated with a minimum distance, which allow to acquire better lubricant retention.
- A load taken at its maximum level $P_y = 10$ N promotes an adhesive wear mechanism, while a minimum level of the load ($P_y = 1$ N) leads to an abrasive wear mechanism.

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Declarations

Conflict of interest The authors declare no competing interests.

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