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Study and evaluation of fretting critical slip conditions by applying the design of experiments method

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Abstract

Tribological systems are complex systems that require a multi-disciplinary (mechanical, material, physico-chemical) approach where numerous influence factors can be involved. To characterize a contact couple, the intrinsic parameters of the materials as well as the parameters related to the contact loading and the surrounding environment need to be taken into account. Fretting analysis, by means of running condition-fretting maps (RCFM), allows the behavior of the contact couple to be taken into account and to predict the boundary between partial slip and gross slip conditions. This article presents the study of a steel/polycarbonate couple during fretting tests. The study was carried out by performing a complete factorial experiment. This method has the advantages of reducing the number of experimental trails and of obtaining the internal laws of dependence, which highlight the influence of the significant factors of the fretting process on the tribological behavior of the studied contact couple.

Keywords: Polymer; Fretting maps; Complete factorial experiment

1. Introduction

The complexity of tribological systems is determined by the numerous influence factors and by the interdependences between them [1]. These parameters are related to: the loading conditions (contact pressure, displacement amplitude, frequency, number of cycles), the characteristics of the first bodies (materials nature, surface state, physico-chemical properties, geometry) and the contact nature (dry, mixed, lubricated friction). Previous research in this field has succeeded in elaborating original concepts about the phenomena and the mechanisms that take place during fretting tests [2,3]. Definition of the loading conditions is accomplished by representing the variation of the tangential force Q with respect to the displacement amplitude δ. The resulting diagrams are named fretting cycle. In order to emphasize the contact evolution depending on the number of cycles N, Colombie [4], introduced a three-dimensional diagram Q–δ–N, named fretting loop. Having the purpose of defining fretting regimes by representing Q–δ cycles on P–δ diagrams. Vingsbo introduced the fretting map concept. Two sets of friction and wear fretting maps have been proposed: the running condition fretting maps RCFM and the material response fretting maps MRFM (Fig. 1). The first one is defined by the nature of the contact conditions, i.e. four fretting regimes, three simple and one mixed [5–10]. By analogy with RCFM, the material response fretting maps MRFM define the main damage (cracking, particle detachment).

For industrial application confronted with fretting problems, RCFM and MRFM furnish valuable information about both the origin and the nature of the degradation processes. By modifying the normal loadings or the displacement amplitude, the most dangerous working regimes can be avoided. To delimit the transition between the partial slip and the gross slip regimes, three quantitative criteria were proposed by Fouvry [11]. One of the studied response function was the energy criterion A defined as

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Nomenclature

A	energy sliding ratio
A_t	transition value of energy criterion
b_i	regression coefficients ($i = \overline{1, 3}$)
b_{ij}	interaction regression coefficients ($i = \overline{1, 3}; i \neq j$)
E_d	dissipated energy during a fretting cycle
E_t	total energy of the cycle
f	frequency
h	depth of the groove
l	width of the groove
N	number of cycles
p	distance between grooves
P	normal force
Q	tangential force
x_i	influence factors ($i = \overline{1, 3}$)
$\bar{y}$	estimated value of the objective function

Greek symbols

δ	displacement
μ	friction coefficient in gross slip conditions or pseudo friction coefficient in partial slip conditions

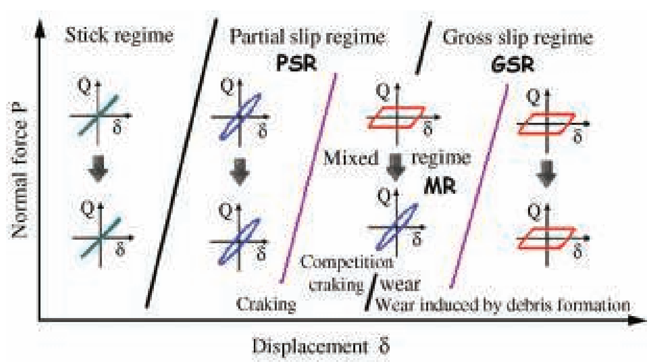


Fig. 1. Running condition and material response fretting maps [11].

the ratio between the dissipated energy (E_d) and the total energy of the cycle (E_t) (Table 1).

In this paper the authors present a new method for describing the behavior of a contact couple during fretting tests. Beginning from one of the transition criterion for partial slip/gross slip regimes defined by Fouvry [3] and utilizing a statistical computing method, the RCFM can be easily obtained.

This paper presents the application of the design of experiments method for describing and characterizing the behavior of a steel/polymer contact during the specific fretting tests. Two different polymer samples were investigated: the first, with a smooth, mechanically prepared surface and the second, having the textured, parallel groove surface, obtained by laser engraving.

The experimental data processing by a suitable computing procedure allowed:

- an empirical mathematical modelling and hierarchical arrangement of involved factors influencing the energy criterion adopted for the fretting slip transition evaluation;
- the direct and easy RCF mapping, giving the boundary between partial slip and gross slip conditions.

2. Experimental conditions

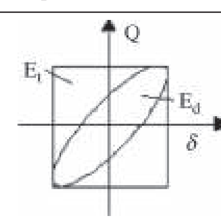
The contact geometry is cylinder on a plane. The cylinder, made of bearing steel (100Cr6 steel), with hardness HRC 60, has a 20 mm diameter and a 3 mm height. The plane sample, made of amorphous polycarbonate has the dimensions (20 mm × 30 mm × 10 mm). For a more complete investigation of the contact couple, two series of experiments were been accomplished:

- using a sample with a smooth contact surface;
- using a sample having a textured contact surface.

The sample with the textured surface presents parallel grooves obtained by laser processing (Fig. 2a) [12]. The grooves dimensions are: width $l = 0.4$ mm, depth $h = 0.4$ mm and the distance between grooves is $p = 0.8$ mm (Fig. 2b). The fretting movement direction is perpendicular to the groove direction (Fig. 2c).

The tribometer used is based on an electromagnetic exciter (Fig. 3). The cylindrical sample is subjected to alternating movement, having amplitudes δ between ±3 and ±500 μm and frequencies f between 10 and 30 Hz. The normal force P can be modified between 10 and 200 N. Fretting tests were realized without lubrication. The measured values of the normal force P, the tangential force Q as well as the displacement amplitude δ were acquired and processed by Labview dedicated

Table 1
The energy criterion A [3]

Expression	Critic transition value	Representation
$A = \frac{E_d}{E_t}$	$A_t = 0.2$; $A < A_t$ = > partial slip regime; $A > A_t$ = > gross slip regime	

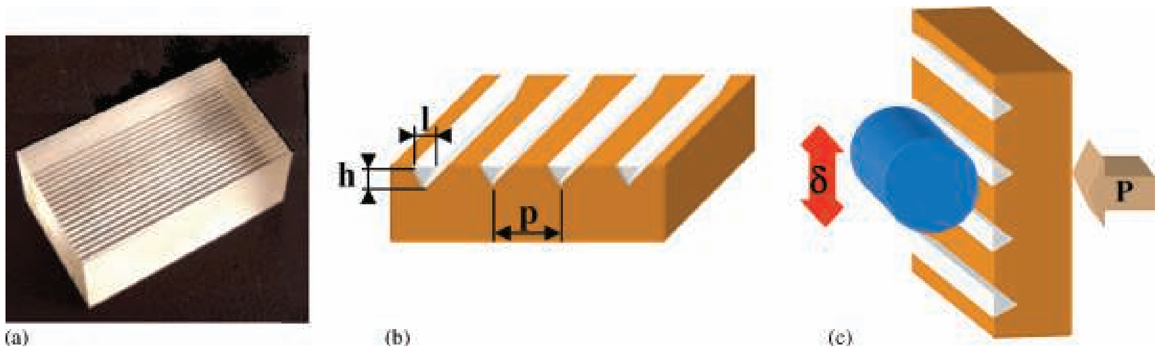


Fig. 2. Textured surface: (a) photograph; (b) schema; (c) schema of the contact.

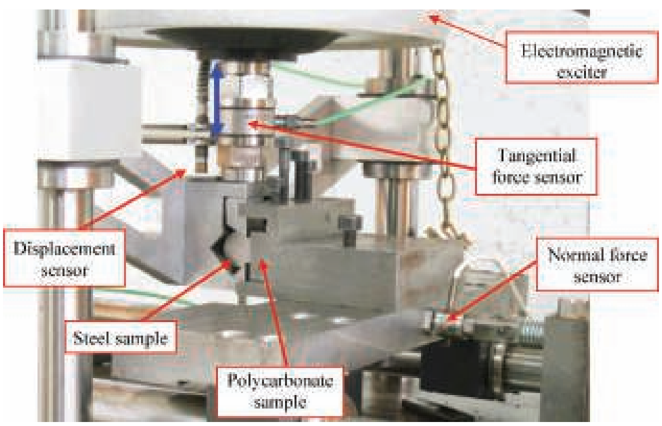


Fig. 3. Fretting device.

software. The software permits tracing the evolutions of the friction pseudo-coefficient ($\mu = Q/P$), the energy criterion A (Table 1) as well as the fretting loops.

3. Experiments design

The empirical mathematical modeling of the bearing steel/polymer couple fretting process was achieved by designing and performing a two-level complete factorial experiment EFC 2^3 [13–15]. The choice of an active experimental program with respect to a classical one, lead to several advantages, such as: the reduced number of runs, the important reduction of the calculus procedure, the increased estimation precision of the regression coefficients. All the fretting tests were performed for $N = 50{,}000$ cycles. The acquisition and the computing of the experimental data occurred after each 100 cycles.

For the designed factorial experiment the value of the A criterion was considered at the following numbers of cycles N: 5000, 10,000, 15,000 and 20,000. The influence factors selected for the fretting tests were:

- $x_1 \Rightarrow$ the normal force P [N];
- $x_2 \Rightarrow$ the displacement amplitude δ [μm];
- $x_3 \Rightarrow$ the frequency f [Hz].

The coordinates of the central point, the variation range and the levels of the influence factors in the factorial experiment were chosen taking into account previous studies [10,16–18] (Table 2).

For practical considerations, regarding the interpretation and the utilization of the expected model, a polynomial mathematical function $\tilde{y}$ as follows was selected:

$$\tilde{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (1)$$

where $\tilde{y}$ is estimated value of each modeling function.

The experimental program, containing all possible combinations of the selected factors levels is presented in Table 3. For each surface, the complete factorial experiment consists of eight runs. The finding of the experimental error associated with the response function and the validation of the results obtained required two additional runs (9, 10 and 19, 20), realized in the central point of the experiment.

4. Experimental results

The experimentally determinate values of the investigated objective function – energy criterion A – in giving conditions, are represented in the right part of Table 3. The experimental

Table 2
Levels of the influence factors

Influence factor	Coded value	Physical value		
		$x_1 \equiv P$ [N]	$x_2 \equiv \delta$ [μm]	$x_3 \equiv f$ [Hz]
Center point	0	30	200	15
Range	Δj	20	100	5
Lower level	−1	10	100	10
Upper level	+1	50	300	20

Table 3
The experimental program

No. run	Energy criterion A										
	Influence factors			Smooth surface				Textured surface			
	$x_1 \equiv P$ [N]	$x_2 \equiv \delta$ [μm]	$x_3 \equiv f$ [Hz]	$N = 5000$	$N = 10{,}000$	$N = 15{,}000$	$N = 20{,}000$	$N = 5000$	$N = 10{,}000$	$N = 15{,}000$	$N = 20{,}000$
1	10	100	10	0.392	0.296	0.281	0.271	0.228	0.199	0.175	0.164
2	50	100	10	0.201	0.211	0.212	0.187	0.184	0.180	0.176	0.167
3	10	300	10	0.662	0.522	0.438	0.398	0.284	0.282	0.279	0.280
4	50	300	10	0.196	0.187	0.182	0.173	0.194	0.166	0.180	0.181
5	10	100	20	0.266	0.248	0.215	0.192	0.219	0.150	0.125	0.093
6	50	100	20	0.082	0.042	0.042	0.037	0.123	0.118	0.123	0.107
7	10	300	20	0.305	0.242	0.233	0.224	0.216	0.173	0.141	0.128
8	50	300	20	0.052	0.065	0.121	0.149	0.217	0.161	0.214	0.195
9	30	200	15	0.188	0.186	0.166	0.139	0.227	0.171	0.183	0.184
10	30	200	15	0.194	0.191	0.174	0.141	0.215	0.182	0.178	0.180

Table 4
Regression coefficient values

Regression coefficients	Energy criterion A							
	Smooth surface				Textured surface			
	$N = 5000$	$N = 10{,}000$	$N = 15{,}000$	$N = 20{,}000$	$N = 5000$	$N = 10{,}000$	$N = 15{,}000$	$N = 20{,}000$
b_0	0.402	0.311	0.341	0.356	0.2286	0.2824	0.2912	0.2845
b_1	-5.28×10^{-3}	-2.75×10^{-3}	-2.72×10^{-3}	-3.59×10^{-3}	-5.25×10^{-4}	-1.86×10^{-3}	-3.02×10^{-3}	-2.8×10^{-3}
b_2	1.62×10^{-3}	1.14×10^{-3}	5.95×10^{-3}	3.58×10^{-4}	4.05×10^{-4}	3.24×10^{-4}	3.19×10^{-4}	4.34×10^{-4}
b_3	-7.05×10^{-3}	-3.96×10^{-3}	-6.21×10^{-3}	-7.59×10^{-3}	1×10^{-4}	-8.88×10^{-3}	-0.0114	-0.013
b_{12}	-2.10×10^{-5}	-1.41×10^{-5}	-7.75×10^{-6}	-3.81×10^{-6}	-2.5×10^{-6}	-4.81×10^{-6}	-1.56×10^{-6}	-3.06×10^{-6}
b_{13}	1.37×10^{-4}	2.62×10^{-5}	2.37×10^{-5}	4.93×10^{-5}	-6.5×10^{-5}	1.13×10^{-4}	2.15×10^{-4}	2.21×10^{-4}
b_{23}	-3.20×10^{-5}	-2.25×10^{-5}	-4.00×10^{-6}	3.87×10^{-6}	-1.65×10^{-5}	-7.5×10^{-7}	-2.5×10^{-7}	-1.75×10^{-3}

data were processed using the principles presented in [13–15], using STATGRAPHICS software [19]. The software allows the estimation of the regression coefficients of the model (1), which are presented in Table 4. The coefficients were determined for the physical values of the influence factors and they show the influence of the three selected factors and of their interactions on the objective functions. The sign and the value of each coefficient indicate the direction and the amplitude of the corresponding influence.

STATGRAPHICS software also permitted the hierarchical arrangement of both influence factors and interactions, based on their effects, using the Pareto Charts (Figs. 4 and 5). The study of the factors influence, considered like independent variables in the performed experiment, was carried out taking into account the regression coefficients values b_i, b_{ij} ($i, j = \overline{1, 3}$; $i \neq j$) of the model (1) (Table 4). The effects values generated by these factors (Figs. 4 and 5) and the corresponding response surfaces (for examples Figs. 6 and 7) show the following:

1. In the given conditions, increase of the normal force P and of the frequency f is determining the decreasing of A criterion and, therefore, the displacement to a mixed and partial regime. The growth of the displacement amplitude has an opposite action, increasing the values of A criterion. The most influential factors were P and f. The most important interactions between the factors were observed in the smooth samples for P and δ and in the textured samples for P and f;
2. The statistical significance of the influence factors diminishes with increase of number of cycles, the diminution being more emphasized in the textured samples.

Fig. 4 shows the Pareto Charts for the polymer sample without laser grooves. The effects situated under the dotted line represented in the figures mentioned above are statistically insignificant:

- at $N = 5000$ and at $N = 10{,}000$ cycles: two factors, the normal force P and the frequency f, have a significant influence on A criterion (Fig. 4a and b);
- at $N = 15{,}000$ cycles: a single factor, the normal force P, has a significant influence on the A criterion (Fig. 4c);
- at $N = 20{,}000$ cycles: none of the influence factors is statistically significant (Fig. 4d).

The Pareto Charts for the textured polymer surface (Fig. 5) have a similar evolution of the fretting process with Fig. 4. But, in this case, the statistical significance of the influence factors is more rapidly lost, after a lower number of fretting cycles. More over, a change of the hierarchy of the influence factors occurs during the fretting test. This fact may be explained by the complexity of the degradation mechanisms and processes, involving additional influence factors in the case of textured surfaces. It is important to note that at $N = 10{,}000$ cycles, the single significant influence factor remains the frequency f.

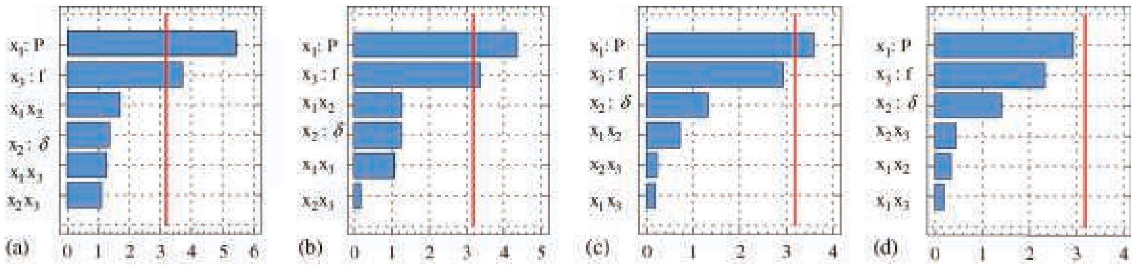


Fig. 4. Pareto Charts for the smooth surface: (a) $N = 5000$ cycles; (b) $N = 10,000$ cycles; (c) $N = 15,000$ cycles; (d) $N = 20,000$ cycles.

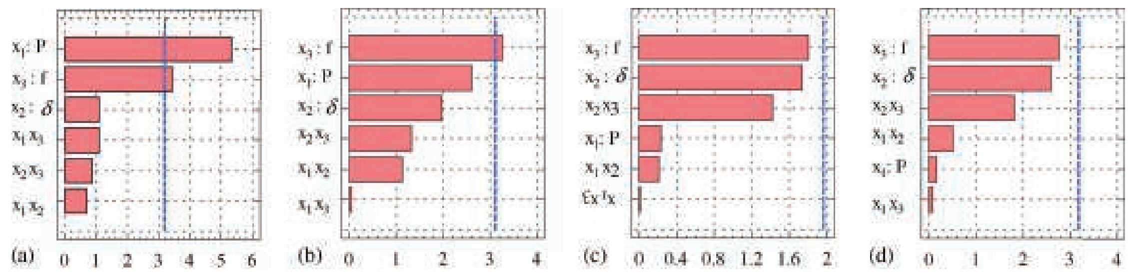


Fig. 5. Pareto Charts for the textured surface: (a) $N = 5000$ cycles; (b) $N = 10,000$ cycles; (c) $N = 15,000$ cycles; (d) $N = 20,000$ cycles.

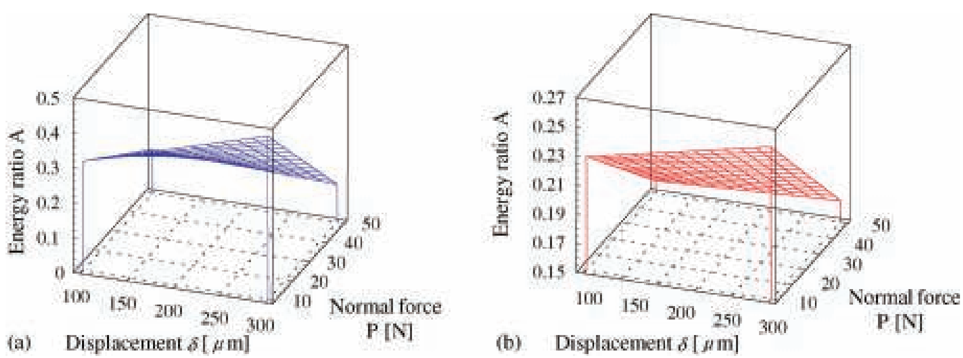


Fig. 6. Response surfaces for the energy criterion A ($f = 15$ Hz, $N = 5000$ cycles): (a) smooth surface; (b) textured surface.

Using these models, the response surfaces of the objective functions can be represented, considering two influence factors. The response surfaces for the energy criterion A with respect to the normal force P and the displacement amplitude δ are represented in Fig. 6.

By sectioning the response surfaces using horizontal planes, parallel with the independent variables plane, the contour plots for the energy criterion A were obtained (Fig. 7).

By choosing the section plane level at 0.2 (the transition value of the partial slip/gross slip regimes), the diagram can be used

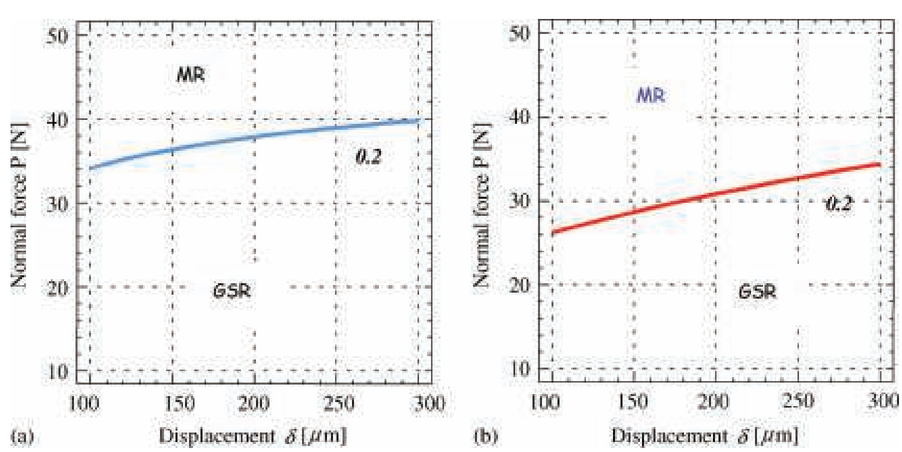


Fig. 7. Running condition fretting maps ($f = 15$ Hz, $N = 5000$ cycles): (a) smooth surface; (b) textured surface.

like a running condition-fretting map RCFM. We can see that the gross slip domain for the textured surface is smaller than the one for the smooth surface. Also, the treatment of the polymer surface is conducing to degradation mechanisms developed principally by cracking, which is specific to the mixed regime MR.

5. Experimental results analysis

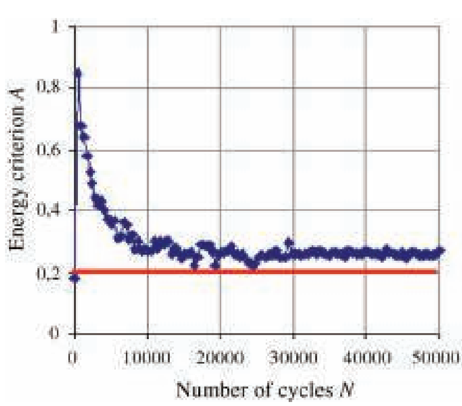
The adopted response function in the performed experiment, the energy criterion $A = E_d/E_t$, defining transition between the partial and total slip regimes, is a measure of the dissipated energy in the contact couple. Theoretically, A criterion and the friction pseudo-coefficient μ have an approximate opposite evolution. Thus, when the interaction of the contact surfaces is weak, the friction coefficient is low and the dissipated energy, and therefore A are high (gross slip regime). This is the characteristic situation at the start of the fretting process (low N). In contrast, when the interaction of the contact surfaces is intensified (with increasing N), by means of deformation, cracking, wear and material transfer processes, the friction coefficient increases and the dissipated energy in the couple decreases.

Thus, at settled normal force P and displacement amplitude δ, A criterion has a decreasing trend, showing the evolution of the friction couples to a regime with a minimum dissipated energy. The analysis of the A criterion values, experimentally determined (Table 3), permits the following observations:

1. By suitable choice of the considered influence factors levels, conditions for the development of two slip regimes have been achieved, namely the gross slip regime GSR (test no. 3) and the mixed regime MR (test no. 2, 4, 5, 6, 7, 8, 9 and 10). Meanwhile, in the case of the no. 1 (Fig. 8) runs the developed regimes were influenced by the surface state (GSR, for the smooth samples, MR for the textured samples). In both cases we can observe a decreasing of A criterion; in the case of smooth samples this criterion stays up to partial slip/gross slip transition value $A_t = 0.2$ ($A > A_t$), while for the textured surfaces it passes under this limit value ($A < A_t$). Generally speaking, in the given conditions, the contact couple with the smooth samples works in one non-stabilized gross slip regime more than the couple with the textured surface.
2. The variation range of the values of the energy criterion A was substantially greater for the smooth samples [0.037–0.662] than for the textured samples [0.093–0.284], which shows the superior stability of the friction couples in the second case;
3. An increase in the loading number of cycles N leads, as a rule, to a diminishing of the A values, which corresponds to the previous considerations mentioned above.

The maximal value for the ratio A corresponds to low forces and high displacements. This observation is consistent with the bibliographic results [5,7,10,18]. We can also observe that the maximal value of the energy criterion A for the smooth surface is greater than the maximal value achieved in the textured surface case. This is a new approach of the running condition fretting maps (Figs. 9 and 10):

- in the given conditions, the displacement amplitude δ is never a statistically significant factor. This result can be explained by the decrease of the real displacement between the two first bodies, after a few hundreds of cycles, that is specific in the case of the mixed regime;
- until a certain value of number of cycles (10,000 for smooth surface, 5000 for textured surfaces) the contact couple works under the influence on the initial loadings. The third body then starts to appear. For these mentioned domains, it is possible to plot a great number of RCFM, corresponding to different pairs of values for frequency f and number of cycles N;
  - for some domains (10,001–20,000 cycles for the clean surface, 5001–10,000 cycles for the textured surface) the third body has a more important role in comparison with that of the initial fretting parameters, which become less influential. Only the normal force for clean surfaces and the frequency for the treated surface are statistically significant.
  - from 20,000 cycles for clean surfaces and 15,000 cycles for the textured surface the behavior of the contact couple is influenced only by the evolution of the third body. The fretting parameters are statistically insignificant. In that case, there is single running condition fretting maps RCFM (Figs. 9 and 10).



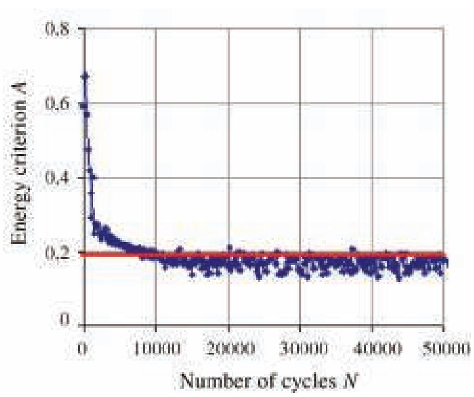


Fig. 8. Energy criterion A ($P = 10$ N, $\delta = 100$ μm, $f = 10$ Hz) (run no. 1): (a) smooth surface; (b) textured surface.

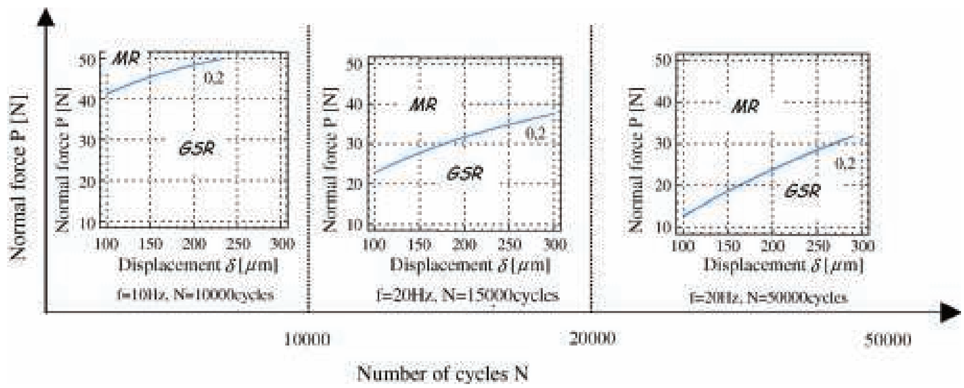


Fig. 9. The running conditions fretting maps for the smooth surface.

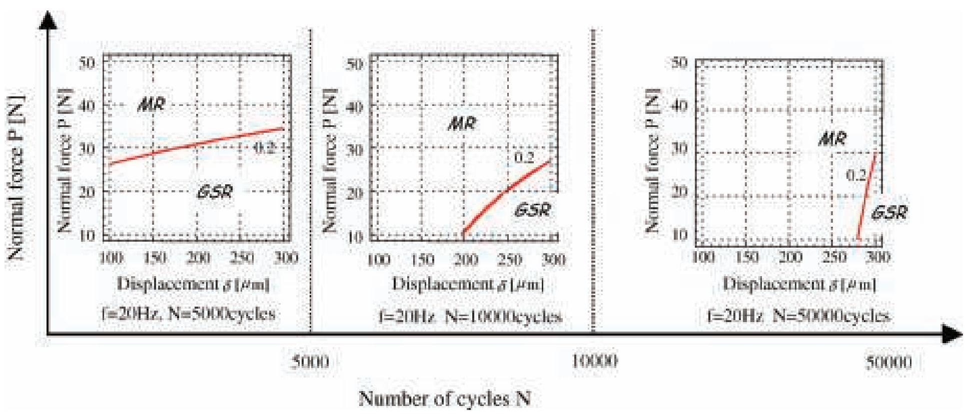


Fig. 10. The running conditions fretting maps for the textured surface.

6. Conclusions

The complete factorial experiment represents a simple and efficient method for the study of the tribological behavior of the steel/polycarbonate couple. This method has the advantages of reducing the number of experimental trials and of obtaining the internal laws of dependence, which highlight the influence of the significant factors of the fretting process on the energy criterion *A*. Furthermore, it permits easy determination of the running condition fretting maps RCFM, which emphasize the working regimes. By applying a surface treatment consisting of laser grooves on the polycarbonate samples, the transition line for mixed/non-stabilized gross slip has moved, enlarging the domain of mixed regime of the contact couple.

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