WEAR RATE FLUCTUATION OF A SLIDING SYSTEM POLYMER-STEEL UNDER THE EFFECT OF FIXED AND FREE JOURNAL BEARINGS

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Abstract. *This study aims discuss an Engineering criteria to assess the performance and quantify until that level it insignificant the unbalancing in the radial direction of a polymer-steel system o the wear rate of this tribological pair. The importance of the research is identifying lower and upper limits for a balanced running of this system. This type of information is useful in the analysis of the life cycle of a system designed considering the wear under some unbalanced conditions and constituting of an automatic trigger for sure a reliable functionality. The test rig developed is presented as also as the results relative to two system configurations of two journal bearings: (1) FrL-FrR, (Free the left, Free the right bearing), (2) FiL-FiR (Fixed the left, Fixed the right bearing). The dynamic response of the system was measured using a microcomputer based on a Fourier Analyzer system. The polymeric materials were analyzed by SEM (Scanning Electron Microscopy) to identify the main wear mechanisms. It was recognized that there was a non-linear relation between unbalancing conditions of the rotating AISI 1045 and AISI 316 stainless steel counterbodies sliding against tested samples of NBR, PTFE and PTFE composites and the temperature next to the contact zone.*

Keywords*: tribology, wear, dynamic response*

1. INTRODUCTION

Systems vibration has been investigated by a variety of authors, but its influence on the tribological behaviour of thermoplastic polymer not have been easily found. Chowdhury *et al* (2007) make a literature review and mentioned that vibration can increase or decrease the wear rate depending from materials pair involved. They studied the influence of the frequency of vibration and relative humidity from mild steel and verified that the wear rate was significantly higher at no vibration.

The combined action of friction heating and material deterioration has attracted the attention of tribologists to the thermal-tribological behaviour. The friction in dry sliding generates frictional heating which is responsible for temperature increases of the sliding components.

Khedkar et al (2002) studying sliding wear of polytetrafluorethylen (PTFE) composites affirms that the tribological behavior of polymers and polymer composites can be associated to their viscoelasticity and temperature related properties. Sliding contact of two materials results in heat generation at asperities and, hence, increases the temperature at the interface. Thus, the adhesive wear resistance of the material depends upon (a) the quantity of the heat generated (b) the way in which this heat is dissipated and (c) the ability of the material to maintain its integrity at the resultant temperature. So, it is important the monitoring of the contact temperature.

The response of the variation in the stiffness from system of sliding wear is investigated through of the freedom from bearing. The interaction between the stiffness of the bearing system in radial direction and the friction heating is considered.

2. EXPERIMENT

2.1 Sliding wear testing

An innovated apparatus was developed. The tribometer had two unlubricated journal bearings that supported the counterbody cylindrical shaft. Due to option of change in the bearing position was possible to vary, horizontally, the stiffness from system in the normal direction to coupon. The tests could assume four configurations of these two bearings: (1) FrL-FiR (Free the left, Fixed the right bearing), (2) FiL-FrR, (3) FrL-FrR, (4) FiL-FiR. A frequency inverter was used to vary the sliding velocity. The tests were carried out in the scheme cylindrical shaft – flat sample (Figure 1). In the developed sliding wear tester the counterbody cylindrical shaft was fixed at the ends and was driven by an electric motor. A polymeric flat coupon was mounted vertically on a pivoted arm and was loaded against the shaft by a dead weight. A unidirectional accelerometer B&K was used to measure the displacement from counterbody in the direction normal to coupon.

Dry sliding was performed under environment conditions with relative humidity between 40 and 60%, at a rate of 0.6 ms^{-1}, a normal load of 3.4 N. Continuous tests were carried out with a sliding distance of 3.2 km.

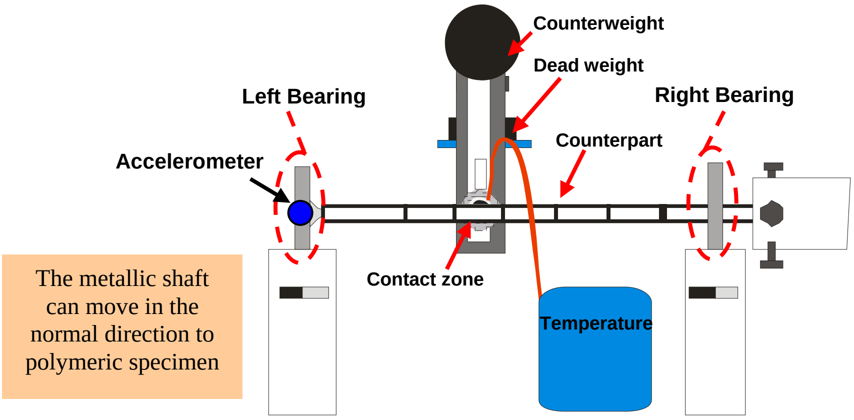

Figure 1. Schematic diagram of the sliding wear tester

The temperature next to the contact was recorded in an acquisition rate of 0.05 Hertz. The worn surfaces after test was analyzed by Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy X-Rays (EDS microanalysis) to identify the predominant wear mechanisms. The coupons were weighted before and after the tests to calculate the wear rate using the Archard Equation as according to Eq. (1).

$$Q = \frac{KW}{H} \qquad (1)$$

Where, Q represent the volume worn per unit sliding distance, W is the normal load and H, the hardness of the softer surface. For engineering applications the quantity K/H is often arranged and called the *dimensional wear coefficient*, *k*. This coefficient k can be quoted in units of m^2N^{-1}.

2.2 Materials

PTFE without filler, PTFE with graphite composite materials and the acrylonitrile-butadiene rubber (NBR elastomer) were studied in this work. These materials were provided in bars which diameters were in a range since 13 until 61 mm. The polymeric coupons had 10 mm of diameter and 12 mm of length. The counterbodies were cylindrical axis of AISI 1045 steel annealed and AISI 316. In the tribological pair NBR-AISI 316 was used NBR from two different manufacturers due to difficulty of rescue samples obtained from a same lot.

Before every test, the surfaces of the coupons and the counterpart ring were smooth with #80, #150, #280, #320, #400, #600 mesh abrasive paper and #80, #150, #280, #320 mesh abrasive paper, respectively, and then cleaned with distilled water in an ultrasonic bath during ten minutes. Metallic counterbody had roughness Ra 10±2μin (according to API 11B standard). The Rockwell B Hardness of the metallic counterbodies was measured. The values were 80.9±7.7 HRB and 75.3±2.8 HRB to AISI 1045 and AISI 316, respectively.

3. RESULTS AND DISCUSSION

Worn surface of the polymeric coupons after sliding against counterbody of AISI 1045 and 316 steel to two bearing positions: FiL-FiR (Fixed Left and Fixed Right bearing) and FrL-FrR (Free Left and Free Right bearing) are presented in the Figs. 2 and 3, respectively.

When rubber with a relatively low tearing strength slid on smooth counterfaces having relatively high coefficient of friction, a wear mechanism arise, which cause roll formation and eventual tearing of the rolled fragment. This type of wear is called frictional wear or rolling wear to some scientists (Zhang, 2004; Stachowiak and Batchelor, 1996). This phenomenon was found in the worn surface of the NBR sliding against AISI 1045 and 316, Fig. 2.

Oxide layer was observed in the worn surface from PTFE with graphite after slides against AISI 1045 steel, confirmed by EDS microanalysis, where were found iron (Fe) and Oxygen (O). Abrasives risk (in the sliding direction) and microdelamination are seen in the PTFE + graphite after sliding against the two counterbodies (Figure 2), this phenomenon was commented by Lima da Silva *et al* (2006).

Severe delamination can be seen in the worn surface from PTFE after slides against the two metallic counterbodies. Abrasive risks in random direction could be seen in the PTFE after tests against AISI 316, as a consequence from low shear strength of this material. The delamination of the PTFE is mentioned by Li *et al* (2002) and Khedkar *et al* (2002) and is explicated by easy formation and breaking of transfer films of low shear strength during sliding.

From SEM micrographs can be observed that the fragmentation of the PTFE was reduced in the presence of graphite flakes that acted as effective barriers to prevent large-scale delamination of PTFE. Authors as Khedkar *et. al* (2002) have discussed the role of graphite as an effective filler material, acting as a solid lubricant so together provide enhanced tribological behavior.

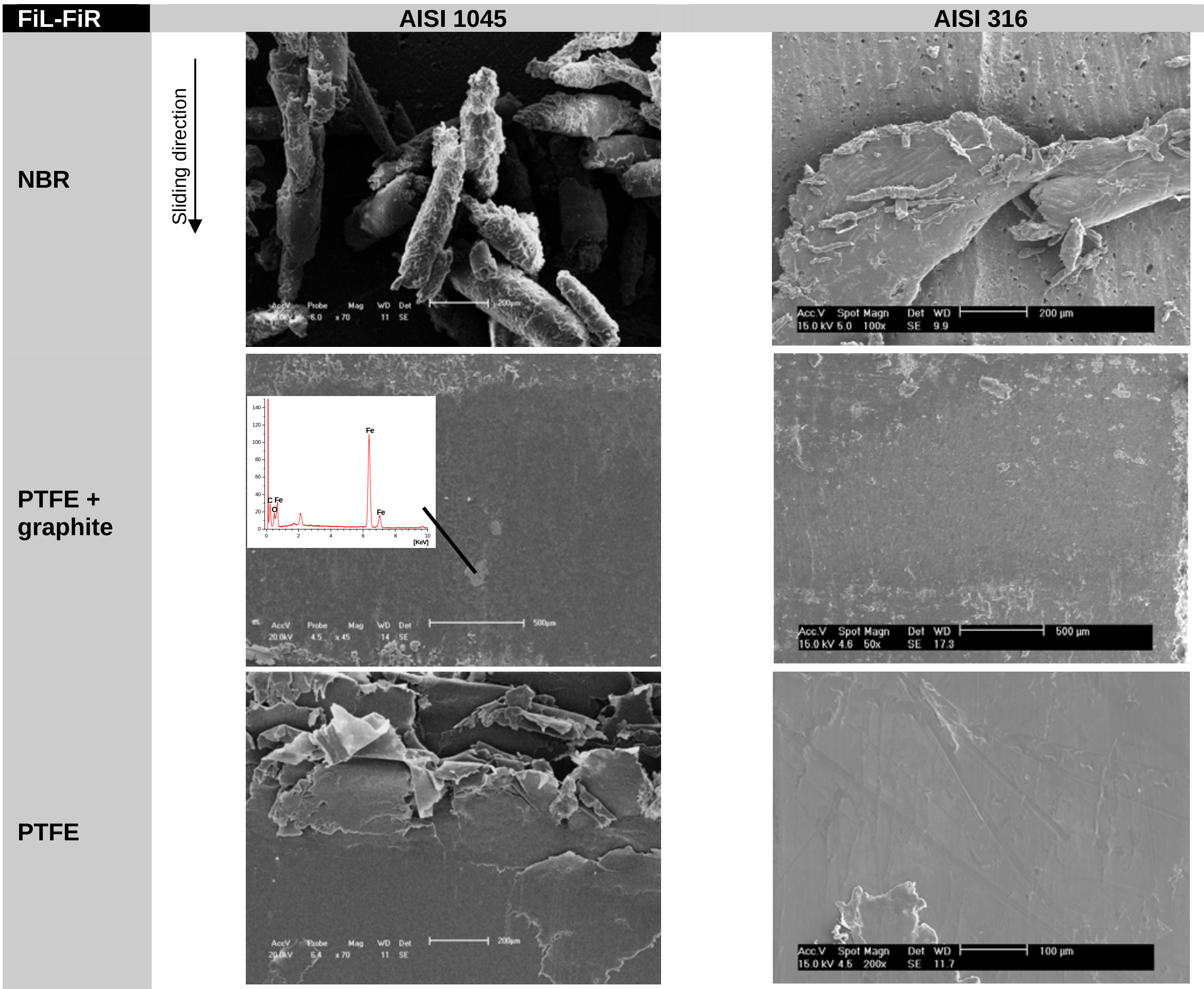

Figure 2. SEM micrographs from worn surface of the coupons after sliding against AISI 1045 and 316 steel in the FiL-FiR bearing configuration

Figure 3 presents the worn surface from polymeric coupons after slides against the AISI 1045 and AISI 316 in the FrL-FrR configuration. Cracks could be observed in the NBR against AISI 1045. Even NBR against AISI 316 presented texture difference that resulted from heating during the test with this counterbody.

Abrasive risks and microdelamination were found in the PTFE with graphite against the two steels. This result was seen in the FiL-FiR configuration.

Flakes of PTFE assumed dimensions larger than 1 mm. As mentioned before, the PTFE presented classic transfer film formation due to molecular and crystalline structure. The crystalline structure consisted of layers of crystalline material between relatively weak layers of amorphous material and this favours deformation of the PTFE in a series of discrete flakes. A block of PTFE in contact with a harder counterface loses material as a series of laminate resulting in low friction but a high wear rate (Stackowiak and Batchelor, 1996). Also was demonstrated that there was strong adhesion between PTFE and metallic counterface.

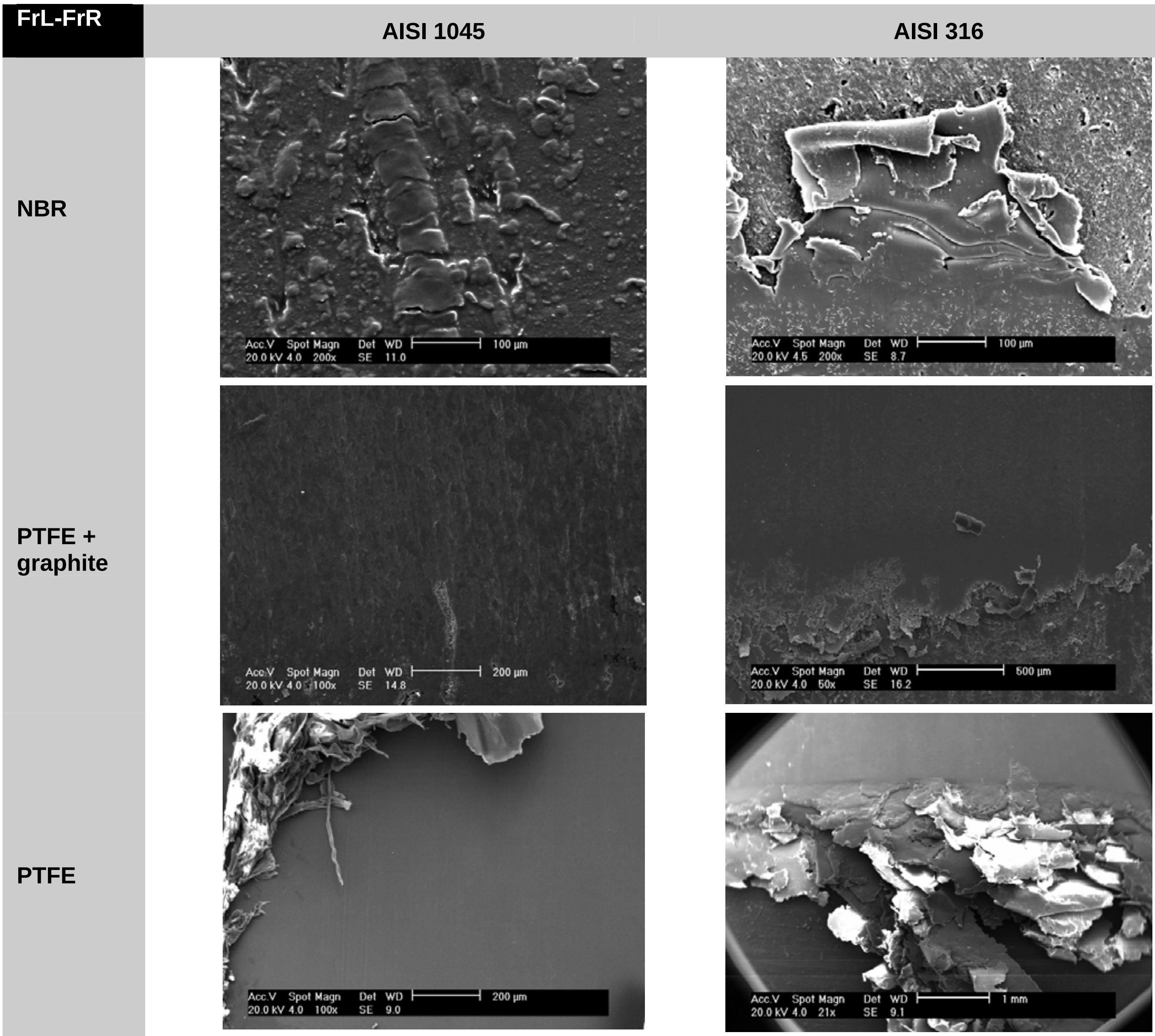

Figure 3. SEM micrographs from worn surface of the coupons after sliding against AISI 1045 and 316 steel in the FrL-FrR bearing configuration

In this investigation, the temperature next to the contact was recorded during the sliding wear testing to each coupon sliding against AISI 1045 and AISI 316, the variation $\Delta\theta$ (temperature next to the contact, Tc, minus the environment temperature, Te) is shown in the Figs. 4-6, in function of the sliding distance to sections from 0 to 1 km (running in), 1 to 2 km and 2-3.2 km.

Figure 4 shows the dissipated heat in function of the sliding distance to NBR coupon against AISI 1045 and AISI 316 steels in the two bearing positions: FiL-FiR (Fixed Left and Fixed Right bearing) and FrL-FrR(Free Left and Free Right bearing). The following behaviours were observed:

1) NBR against AISI 316 presented higher temperature than AISI 1045 in all conditions tested, assuming difference from until 26 ^{o}C. The counterface had considerable influence on the wear of any polymers and a good bearing design included careful specification of the counterface. The counterbody affects the wear of a polymer accord to its hardness, roughness and surface energy (Stackowiak and Batchelor, 1996). By the other side, the friction was associated with the temperature difference observed in the two metallic counterbodies, considering that, in this work, the roughness and hardness from counterfaces were very close (10±2µin Ra to two steels and 80.9±7.7 HRB and 75.3±2.8 HRB to AISI 1045 and AISI 316, respectively). Thus, in this case, the temperature next to contact can be also an indirect measurement of the synergy between the friction and the surface energy.

2) Between 2.0 and 3.2 km, the curves converged to same temperature for the two counterbodies. These results indicated that in the sliding interval mentioned it was reaches the steady-state temperature to NBR in the FiL-FiR and FrL-FrR conditions. Table 1 presents the results of *p-values* obtained by statistical correlation from temperature curves to

NBR using ANOVA from software OriginPro 7.5. Although of the curves converge to same platform, the *p-values* showed that, in a confidence level of 5%, there was a statistical difference between the populations (except to FiL-FiR/ FrL-FrR – AISI 316).

3) Higher temperature fluctuations were found in the condition FiL-FiR bearing in relation to FrL-FrR. In the contact zone, the chain of rubber was stretched in the sliding direction, consequently the friction coefficient increased. When the tangential stress actuating in this zone reached its limiting strength, the friction force gone its maximum and the molecular chain was ruptured. The molecular chain recovered rapidly to the original place and the friction force decreased, as proposed by Zhang, 2004, to whom these processes occur repeatedly and could be the explanation to the temperature fluctuations in the condition FiL-FiR bearing.

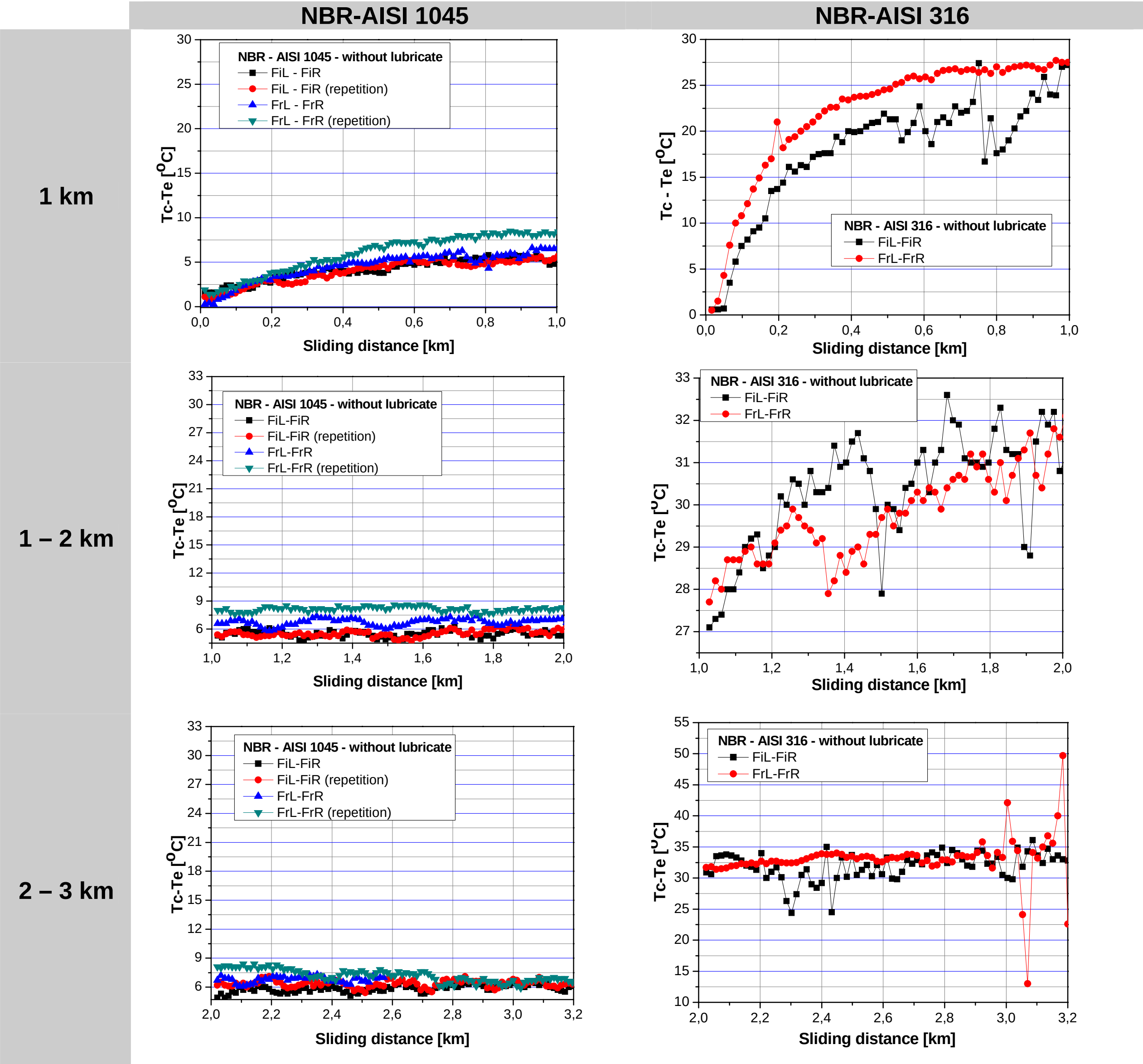

Figure 4. Variation of temperature next to the contact in the sliding testing to NBR coupons against AISI 1045 and 316

Table 1. *P-values* results from statistical analysis ANOVA of the temperature measurements of the NBR

	AISI 1045			AISI 316		
***p-value* (0.0-1.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0.29098				
FrL-FrR	0.10037	0.01356		0.00061		
FrL-FrR (repetition)	0	0	0			
***p-value* (1.0-2.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0.37738				
FrL-FrR	0	0		0.01181		
FrL-FrR (repetition)	0	0	0			
***p-value* (2.0-3.2 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0				
FrL-FrR	0	0		0.15281		
FrL-FrR (repetition)	0	0	0.00008			

At the 0.05 level, the population means were not significantly different.

Figure 5 shows the dissipated heat in function of the sliding distance to PTFE + graphite coupon against AISI 1045 and AISI 316 steels to two bearing positions: FiL-FiR (Fixed Left and Fixed Right bearing) and FrL-FrR(Free Left and Free Right bearing). The following behaviours were observed:

1) As in the NBR, the PTFE + graphite against AISI 316 presented higher temperature than AISI 1045 in all conditions. However, was verified a difference from just 3 ^{o}C.

2) Higher temperature fluctuations were found in the tests with AISI 1045 than AISI 316 steel. This can be seemingly related to surface energy from counterbody. Second Stackowiak and Batchelor (1996) the thickness of the transfer film of polymer depends on the surface energy from metallic counterbody. When the surface energy is low the transfer film is thin and can don’t cover surface uniformly, leaving gaps of exposed metal;

3) In the FiL-FiR configuration, the dissipated heat was higher in the tests with AISI 1045 and AISI 316 (except in a test in the FrL-FrR with AISI 316, where the result was inverted). According to Chowdhury *et al* (2007) under higher vibration conditions there is always more separation between the surfaces. This reduces the contact pressure, momentarily, which causes the reduction of effective normal force and hence reduces abrasion and adhesion wear. So, in the FiL-FiR configuration no there was reduction of effective normal force and this resulted in higher temperature.

Table 2 presents the results of *p-value* from the statistical correlations of the temperature curves to PTFE with graphite. The *p-values* showed in two cases that there wasn’t statistical difference between samples: FiL-FiR repetition/ FrL-FrR in the first kilometer (AISI 1045) and FiL-FiR/ FrL-FrR in 1.0-2.0 km (AISI 316).

Figure 6 shows the dissipated heat as a function of the sliding distance to PTFE coupon against AISI 1045 and AISI 316 steels to two bearing positions: FiL-FiR (Fixed Left and Fixed Right bearing) and FrL-FrR(Free Left and Free Right bearing). The following behaviours were observed:

1) Temperature fluctuations in the tests with AISI 1045 for the two configurations of stiffness. These fluctuations occurred periodically with sinusoidal variations of 2 ^{o}C at each 400 m to FiL-FiR conditions. The oscillation is related with the formation and break of lubricant transfer film of PTFE to metallic surface tending to reduce and to raise the contact temperature, respectively. As observed and commented in the Fig. 5, the surface energy probably affected the formation process of transfer film;

Table 3 presents the results of *p-values* of the statistical correlation from temperature curves to PTFE. The *p-values* showed that in all cases there was a statistical difference between samples with exception to FrL-FrR/FrL-FrR (repetition) to AISI 1045 in the first kilometer.

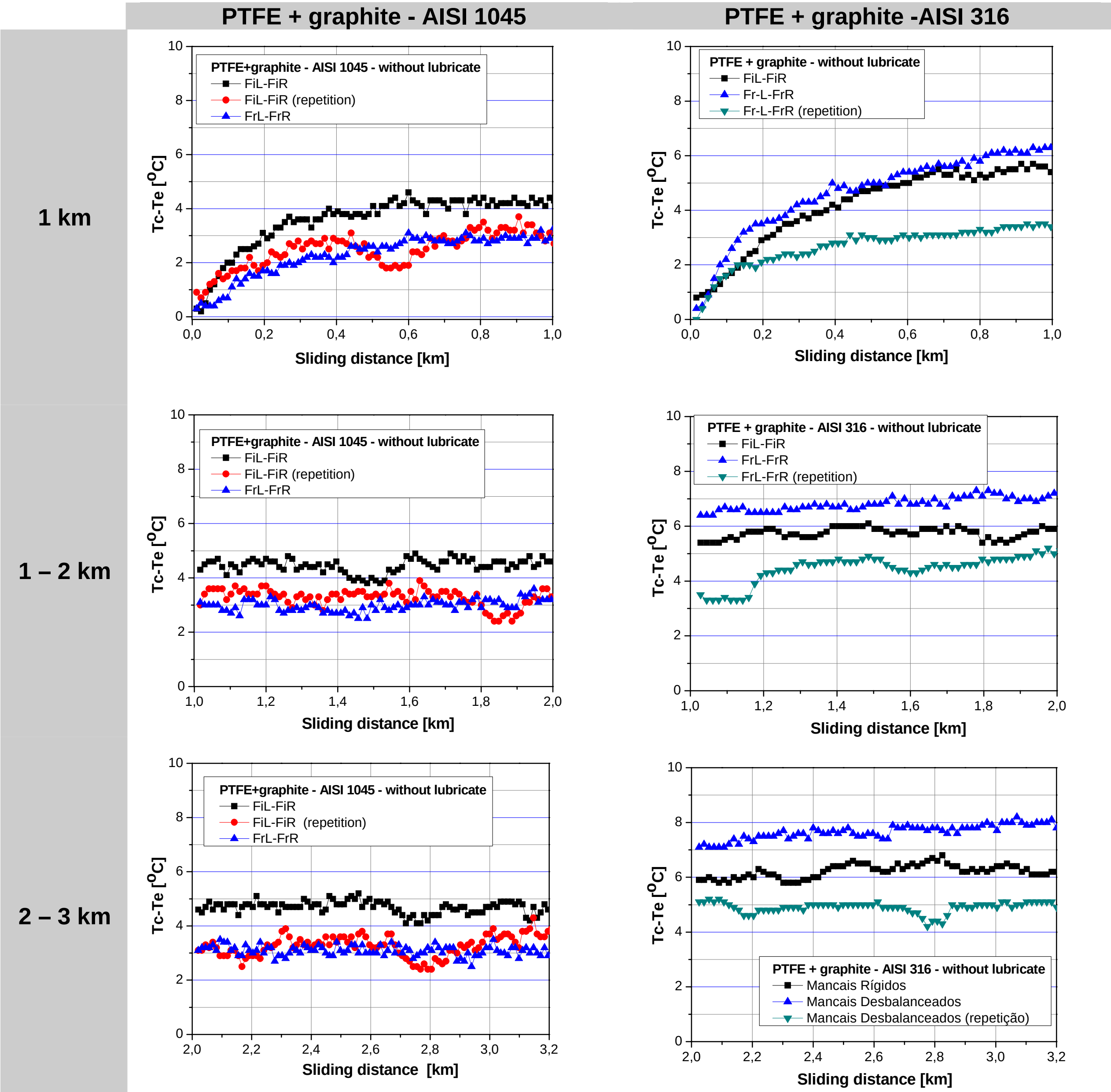

Figure 5. Variation of temperature next to the contact in the sliding testing to PTFE+graphite coupons against AISI 1045 and 316

Table 2. Results from statistical analysis ANOVA of the temperature measurements of the PTFE+graphite

	AISI 1045			AISI 316		
***p-value* (0.0-1.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0				
FrL-FrR	0	0.07322		0		
FrL-FrR (repetition)				0		0
***p-value* (1.0-2.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0				
FrL-FrR	0	0		0.07165		
FrL-FrR (repetition)				0		0
***p-value* (2.0-3.2 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0				
FrL-FrR	0	0.00001		0		
FrL-FrR (repetition)				0		0

At the 0.05 level, the population means were not significantly different.

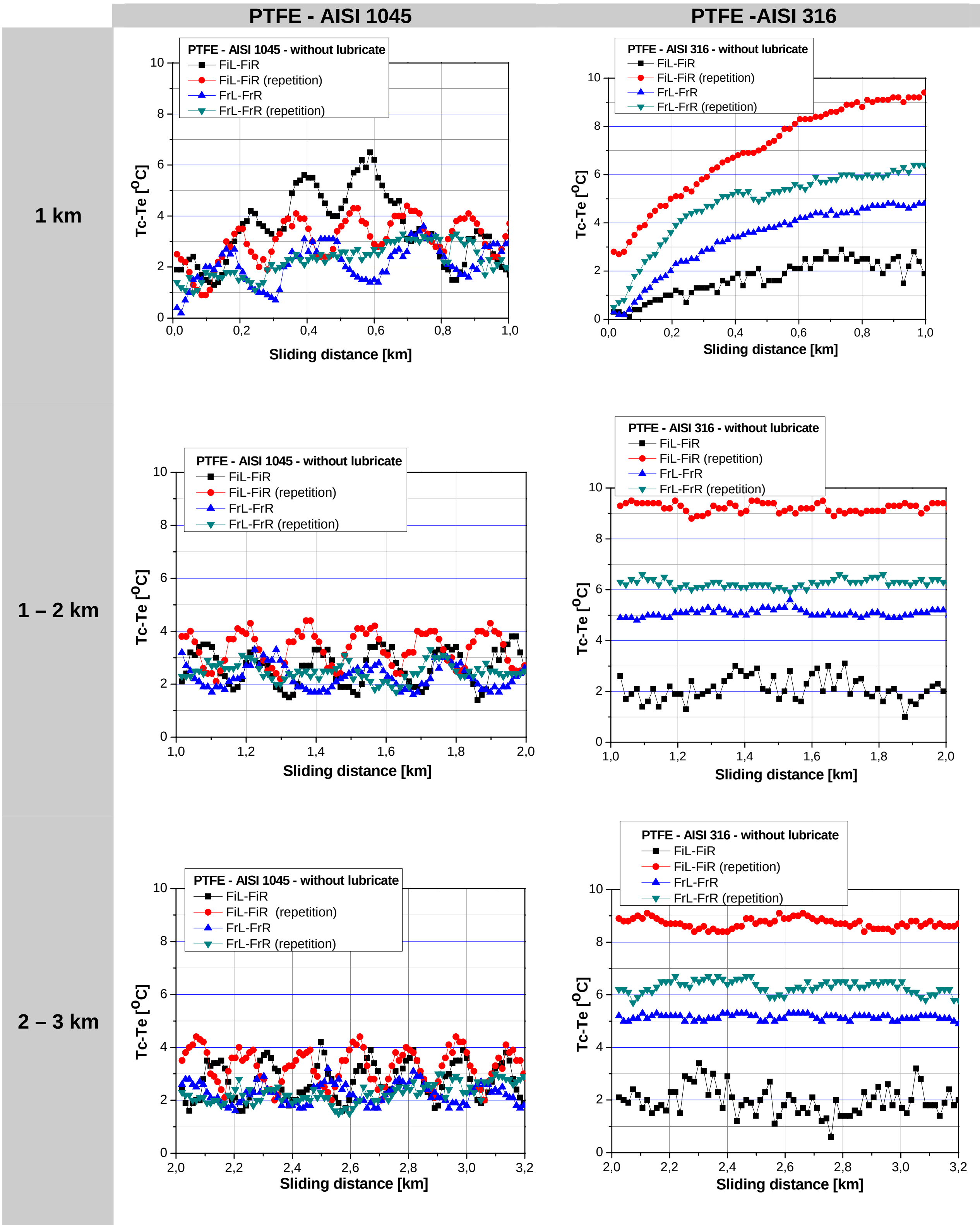

Figure 6. Variation of temperature next to the contact in the sliding testing to PTFE coupons against AISI 1045 and 316

Table 3. Results from statistical analysis ANOVA of the temperature measurements of the PTFE

	AISI 1045			**AISI 316**		
***p-value* (0.0-1.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0.0319			0	
FrL-FrR	0	0		0	0	
FrL-FrR (repetition)	0	0	0.3064	0	0	0
***p-value* (1.0-2.0 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0			0	
FrL-FrR	0.00006	0		0	0	
FrL-FrR (repetition)	0.03948		0.00161	0	0	0
***p-value* (2.0-3.2 km)**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**	**FiL-FiR**	**FiL-FiR (repetition)**	**FrL-FrR**
FiL-FiR		0			0	
FrL-FrR	0	0		0	0	
FrL-FrR (repetition)	0	0	0.04252	0	0	0

At the 0.05 level, the population means were not significantly different.

The wear rate was calculated using the Archard equation from mass loss. Figure 7 shows the wear rate, k, of the polymeric coupons after sliding against the metallic counterbodies in the conditions of higher and minor stiffness. Two bigness order of difference in the wear rate of the NBR against AISI 1045 and 316 was found. This difference occurred due to different manufacturers of NBR against each counterbody. Zhang (2004) commented that properties of NBR depend of the content of acrylonitrile, but pursue this research path deviates the focus of this present work. The resulted of temperature also was affected by NBR commercialized by manufacturers different (Figure 4). These results reaffirm the importance of difference between materials properties when change itself the material sources, also reassert that the temperature measurement is a rapid and significant tool in the comprehension and evaluation of tribological response.

Wear rate wasn't affected considerably by variation from stiffness. Ashby (2000) presented in his *chart 16*, the wear rate in function of the hardness to all Engineering Materials classes, where he shows that the PTFE have a wear rate in the range of 10^{-14} to 10^{-13} m^2N^{-1} in other test configuration. This result was corroborated in the Fig. 7. The PTFE + graphite coupons showed a reduction in the wear rate in relation to PTFE. This result also was anticipated by Ashby.

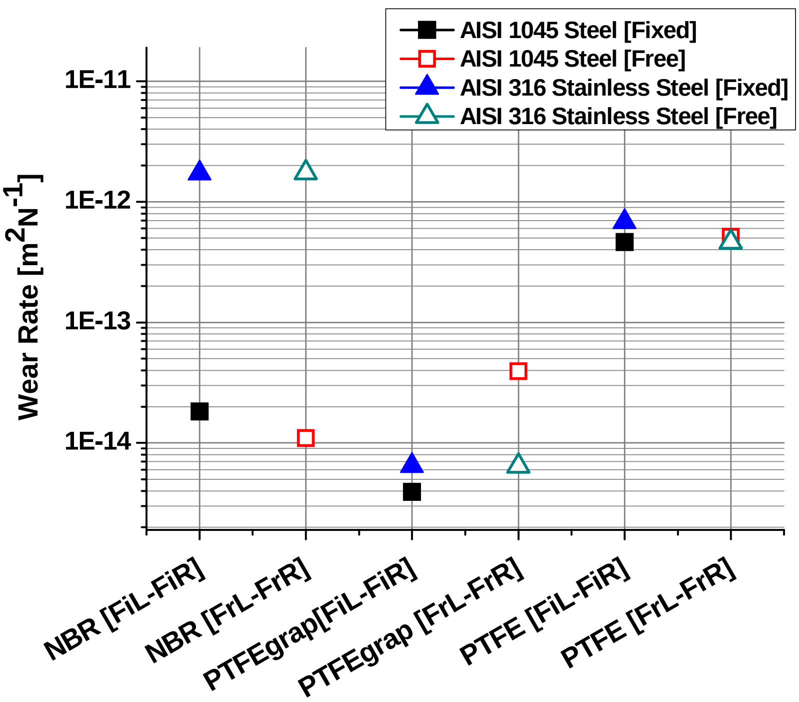

Figure 7. Wear rate from polymeric coupons after tests

4. CONCLUSIONS

A new conception of tribometer has been designed. The present work shows that, under the present experimental conditions,

1. the bearing stiffness has influenced in one magnitude order the wear rate uniquely for PTFE+graphite coupons sliding against AISI 1045 steel;
2. AISI 1045 steel counterbodies supported by free journal bearings sliding against polymer coupons has promoted a wear rate varying one magnitude order for NBR[10^{-14} m^2/N], PTFE+graphite [10^{-13} m^2/N] and PTFE [10^{-12} m^2/N], while under fixed journal bearings these correspondent values were, respectively, $2x10^{-14}$ m^2/N [NBR], $5x10^{-13}$ m^2/N [PTFE] and $4x10^{-15}$ m^2/N [PTFE+graphite];
3. AISI 316 stainless steel counterbodies apparently were independent of free or fixed journal bearings sliding against polymer coupons since that promoted wear rates varying for NBR [$2x10^{-12}$ m^2/N], PTFE [$6x10^{-13}$ m^2/N], and PTFE + graphite [$6x10^{-14}$ m^2/N].
4. Wear rate response corroborated the results of Ashby to all polymers, except the second manufacturer of NBR (used in tests against AISI 316). The importance from difference of materials property when change the material source was reaffirmed and the temperature measurement was rapid and significant in the comprehension of tribological response.

5. ACKNOWLEDGEMENTS

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