Comparison of the wear and the friction coefficient of metallic specimens in reciprocating and rotating lubricated tests

Marcia Marie Maru
mmmaru@usp.br

Deniol Katsuki Tanaka
dktanaka@usp.br

Escola Politécnica da Universidade de São Paulo

Abstract. *This work aims to compare the wear and the friction coefficient results of reciprocating pin-on-plate and rotating pin-on-disk sliding tests. The surface and sub-surface features are presented.The metallic materials used were round-ended AISI 52100 steel pins and SAE 8640 steel plates or disks. Two 100 viscosity index paraffin base oils, with and without additives, were used.The rotating and reciprocating systems was Plint & Partners TE67 machine. The tests were performed with 283 N pneumatic applied load at 184 rpm disks speed or at 4.2 Hz reciprocating plates oscillating frequency immersed in oil bath at 100 ºC temperature. The tests were performed up to 50,000 cycles.The lower values of wear rates and the friction coefficients were observed in the tests with additived oil. The rotating system was less severe than the reciprocating system. The wear mechanism was distinct for rotating and reciprocating tests in the tests with additived oil. Discussions considering differences in the oil flow between the tribossystems are presented.*

Keywords: wear, friction, reciprocating, rotating, additive, lubricated

1. Introduction

It is known that surface interactions control the performance of most mechanical systems and a great part of these operate under lubricated sliding conditions. In this case, the essential role of the lubricant is the wear and friction reduction of the sliding parts. Even a monolayer of lubricant of molecular thickness at the contacting interface is able to change the tribological response of the system (Persson, 1998). Advances in the oil-surface interaction knowledge may allow lubricant and part materials to be developed alternatively with more fundamentally based tribological solutions. In practice, the experimental approach is common for investigating the new alternatives, where the mechanical system is often laboratory simulated. The experimental approach has a critical point: the identification of the relevant tribological variables. In order to minimize the costs in laboratory simulation, simplified tentative solutions are commonly tested. This simplification involves some risk when selecting the relevant variables in a consistent way, either fundamentally or practice based. The identification and understanding of the relevant tribological variables are largely performed through conventional laboratory tribometers. However, it is noticed in general that in studies with lubricated systems the similarity of the lubrication modes between the simulated and the real system is not adequately evaluated. The investigations are likely to be mostly oriented specifically for materials performance, and the lubrication adequacy of the tribossystem in the tribometer to a practical application is less considered.

The conventional laboratory tests are essential since they provide opportunities for basic wear mechanisms studies. For allowing this to be useful in practice, it is necessary to know the existing potentialities and the limitations of these tests. For instance, it is known that four ball tests are able to provide tribological performance results under extreme operating conditions; however, they could not be adequate for evaluating tribological behavior of systems that do not operate in such practical conditions. In the practical sense, as described by Dowson (1997), in order to have real tribossystems adequately simulated in laboratory, it is necessary to know the operation of the real system and their most relevant tribological variables; on the contrary, the laboratory simulation using conventional tribometers can lead to erroneous indications concerning the actual performance. On the other hand, there is also the need to know the potentialities and complexities involved in the conventional tests. Therefore, for improving the practical applicability of the tribological studies performed by conventional machines, it is necessary to investigate the main influences and their effects on the tribological performance in the tests with such machines, not only in terms of operational conditions but also regarding the differences among the systems. In the case of lubricated systems, the lubrication influence characterization is emphasized.

Fundamental research in lubricated sliding is conducted mostly with continuous movement systems, as four ball, ring-on-block and pin-on-disk assemblies. There are also sliding lubricated studies through reciprocating tribometers, called pin-on-plate machines, as seen in investigations by Cavdar (1997), Cutler et al. (1997), Martin et al. (1999) and Maru and Sinatora (2001). The studies in general do not mention why the continuous or the reciprocating system is chosen, excepting the cases based on some similarity among the laboratory system and the actual application being studied (Maru, 1998).

In terms of tribological differences between the continuous and the reciprocating systems related to lubrication, no investigations were found. Concerning dry sliding systems, only a short number of investigations can be found. Some of these showed that both wear and friction are higher for continuous sliding system. Blau and Waluskas (2000) explained the higher wear and friction as caused by the formation of lips at lateral edges of the wear track, called “built-up edge”, more prone to happen in continuous sliding systems. It was also confirmed by Marui and Endo (2001).

As sliding proceeds, depending on the testing conditions, particles interaction in the contact is possible, also resulting in wear and friction changes. Hwang, Kim and Lee (1999) conducted rotating and reciprocating sliding tests with a device to observe particles interaction during the tests. They observed that the friction coefficient increases when a particle is produced at the interface. After the first particle is produced, the formation of other subsequent ones had apparently not modified the friction response. In this case, the friction increase was credited to a ploughing mechanism on the surface caused by the first particle produced. The friction does not increase due to the subsequent particles because they get clustered and, after that, broken. Tests removing the particles out of the contact were also performed, where the friction was reduced. From this study, the authors observed that both wear and friction were higher in continuous sliding tests. They explained this result by the difference in particles clustering, which was more evident for continuous unidirectional sliding.

Odabas and Su (1997) investigated comparative performance between unidirectional and reciprocating sliding using pin on sandpaper and also concluded that wear is lower in reciprocating sliding. In this case, it was explained by the difference among the run distances and by the influence of the presence of particles in the wear track. It was seen that the amount of particles remaining in the contact was larger in the unidirectional continuous tests. The authors explained it mentioning that the track radius of the unidirectional sliding was much smaller than the length of the reciprocating stroke (35 mm to 220 mm), what is certainly related with centrifugal force action on the particles.

On the other hand, reciprocating, compared to unidirectional machines, can be considered as more severe to wear, if the surface inducted stresses are considered. Differently from continuous, reciprocating sliding can induce both tensile and compressive stresses in the surfaces. Ward (1970) studied the reciprocating and rotating tribossystem configurations and their influences on the dry wear of steel bodies. This author observed that the wear under reciprocating sliding condition was higher than in continuous sliding tests. He also observed that the wear regime transition from mild to severe occurred at a lower load for reciprocating sliding. The author related it with two main influences: differences in surface stressing and amount of remaining wear particles in the wear track; in this case, both larger for reciprocating sliding.

In the present investigation, characterizations in the wear and the friction resulting from oil-lubricated reciprocating and rotating tests are presented.

2. Materials and methods

The sliding tests were conducted through a TE67 Plint&Partners tribometer. This machine has devices for reciprocating pin-on-plate (P code) or rotating pin-on-disk (D code) sliding. Figure 1 schematically shows the configurations used.

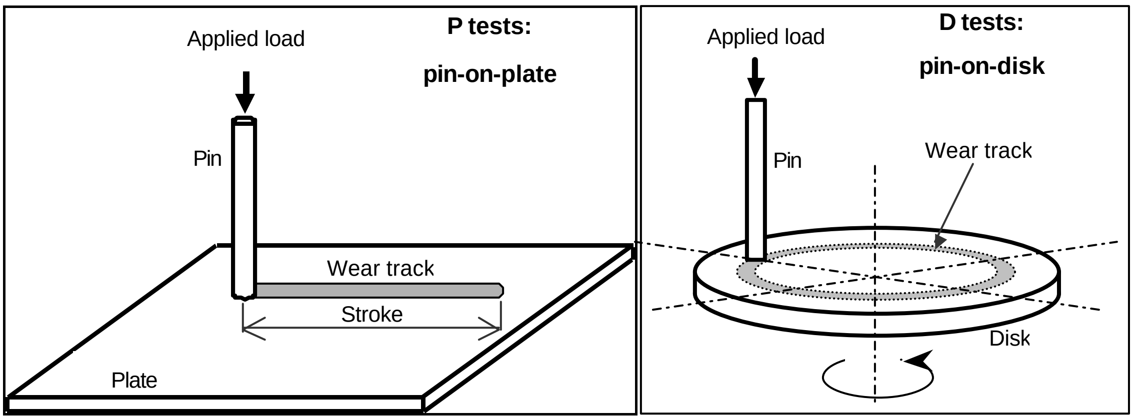

Figure 1: Geometric configuration of the reciprocating and rotating devices used for the sliding tests.

The kinematics of the reciprocating motion is related to the rotating one according to Eq. 1.

$$v = 2 \,.\, \pi \,.\, f \,.\, R \,.\, \mathrm{sen}\,(\theta) \tag{1}$$

Where:

v: velocity of the motor axle of the disk [m/s]

f : disk rotation (or plate oscillation frequency) [Hz]

R: disk track radius (or ½ plate stroke length) [m]

θ: angle of pin circular motion relative to circular track in the rotating system [rad]

In this way, the maximum sliding velocity (V) in the reciprocating motion occurring at mean track length is $V = 2.\pi.f.R$. The mean sliding velocity can be obtained by integrating Eq. 1 from 0 to 180 º, giving $V_{med} = 4.f.R$.

With both devices, the normal loading was applied on the pin pneumatically. The contact between the specimens was immersed in the oil bath heated by electrical resistors positioned under the oil bath. The equipment has electronic sensors to control the normal load, the bath temperature and the disk rotation or the plate oscillation frequency, and to monitor the friction force. The values indicated by the sensors can be stored in data files. In the tests, the data were acquired at every 10 s.

Every test was run with a previous step of 1,200 s (0.33 h) for oil heating, up to 100 ºC, without loading and at the testing velocity. After the previous step, the load (283 N) was applied and the test was stopped after 50,000 pin cycles on the disk (100,000 pin cycles on the plate) were completed. Table 1 summarizes the testing conditions. According with the IRG diagram, which indicates the transition curves among lubrication regimes based on load and velocity values (Gee, Begelinger and Salomon, 1984), the tests were done under mixed lubrication condition.

Table 1: Testing conditions.

Test code	Temperature °C	Load N	Rotational speed, rpm (Frequency, Hz)	Radius mm	Mean velocity m/s	Run distance m	Time h	Cycles
D	100	283	184 (3.1)	11	0.21	3,456	4.5	50,000
P	100	283	250 (4.2)	16 (*)	0.13	1,600	3.3	100,000

(*) This value refers to ½ stroke in the reciprocating motion.

The pin material was AISI 52100, 3 mm diameter and 23.8 mm length. The geometry of the testing surface was rounded with $5{,}5 \pm 0{,}3$ mm radius. The pins are needles rollers (NRA[1] code) used in the rolling bearings produced by INA Brazil Ltda. The measured hardness was 63 ± 0 HRC (25 kg). Figure 2 shows the top view of the pin testing surface. Some morphology similar to microcraters can be noticed. The Ra (mean height of asperities) roughness of the pin surface was 0.1 ± 0.05 μm (1.25 mm measurement length).

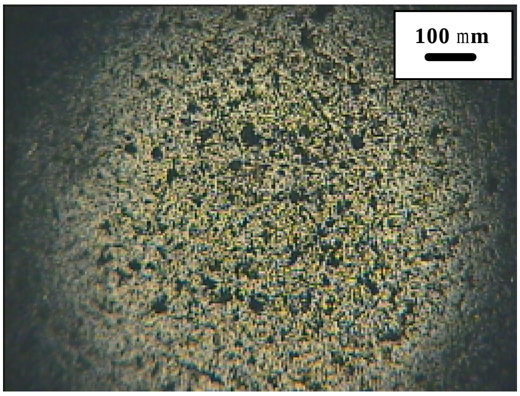

Figure 2: Microscopic observation of the pin testing surface.

The disk and plate material was AISI 8640, quenched and tempered with 48 ± 1 HRC hardness. The disks were machined to 75 mm diameter and 8 mm thickness size and the plates to 58 mm x 38 mm x 4 mm. The surfaces were ground-finished, as shown in Fig. 3. More randomly finished surface is noticed in the disk than in the plate. The Ra roughness value of the disks was 0.65 ± 0.15 μm; the plates had 1.3 ± 0.2 μm.

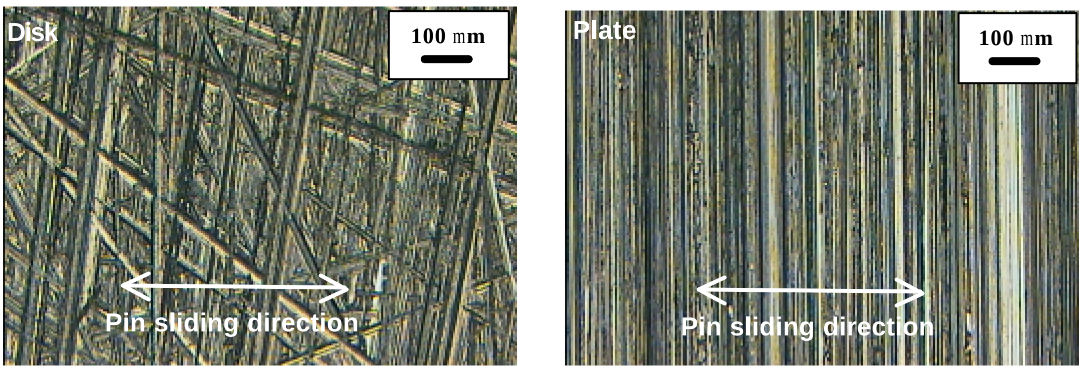

Figure 3: Microscopic observation of the testing surface of a disk and a plate.

[1] BR019 Catalogue, INA needle rollers, Rolamentos Schaeffler do Brasil, 1998.

As lubricant, a parafinnic base oil was used, one with and another without additives. The oil with additive pack is commercialized by BR Distribuidora under EGF 100-PS designation. The additive pack represents less than 3% in mass and is composed by alkyl phosphate, fractions of petrol and sulfured fatty acids with anticorrosive, antirust, antioxidant, anti-wear, extreme pressure (EP) and anti foaming properties[2]. A sample of this oil was analyzed by optical spectrometry of 19 elements, by which the presence of 354 μg/m phosphorus was detected. The oil was also analyzed by infra-red spectrometry, which detected the presence of sulfur in its composition. The oil without additives was Vitrea 100, produced by Shell Company. Both oils have the same viscosity index (VI 100) and are normally recommended for gearbox lubrication. SA code was used for tests without additived oil and CA for tests with additive.

3. Results

The pins and the plates tested surfaces were observed through optical microscopy. Figure 4 shows the results for P SA (reciprocating, oil without additive) tests and Fig. 5, for D SA (rotating, oil without additive) tests. Severe wear is observed, since heavy scratching and plastic deformation are seen in the worn surfaces.

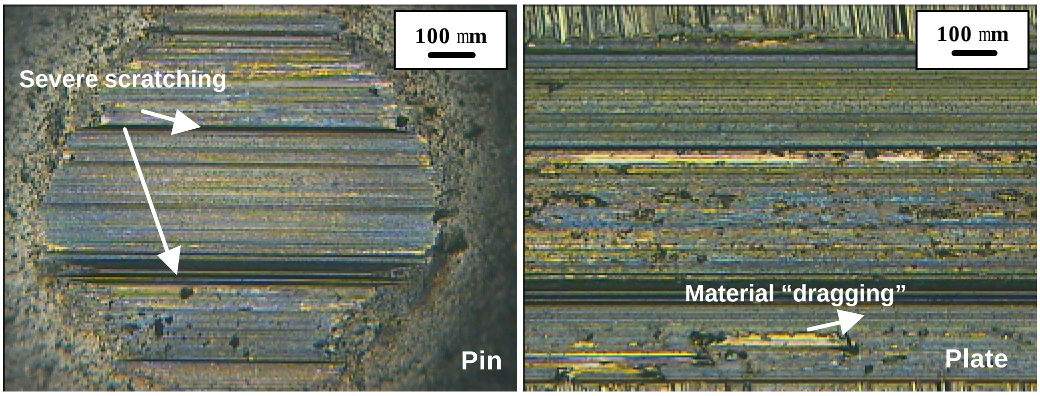

Figure 4: Microscopic observation of the worn surfaces, P SA test condition.

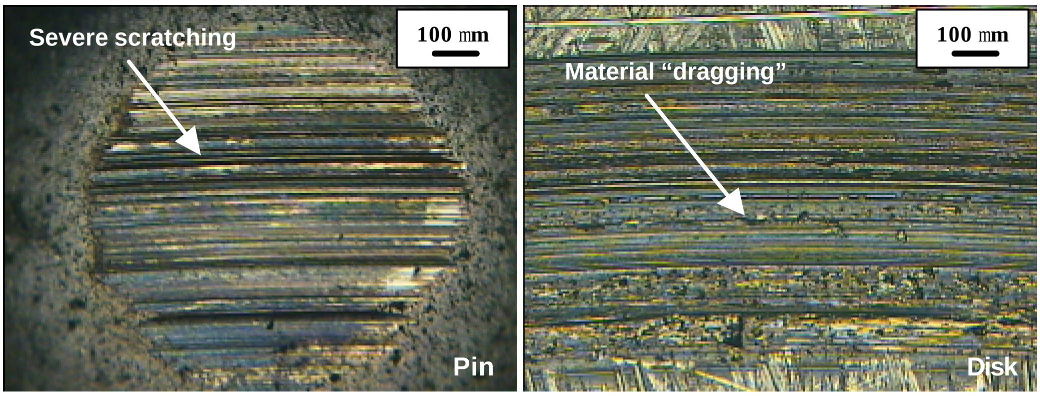

Figure 5: Microscopic observation of the worn surfaces, D SA test condition.

The presence of severe scratching in the pin surface indicates a mechanism of severe abrasion acting on it. In the counter-bodies, areas with material “dragging” are noticed, indicating plastic deformation occurrence on them.

Figure 6 shows the worn profiles of the tested specimens, where surface roughening and higher wear of the plate, compared with the disk, are observed.

[2] Petrobrás Distribuidora S/A Catalogue, Série Lubrificantes – Vol. 1 – Rev. 01 - April/2000.

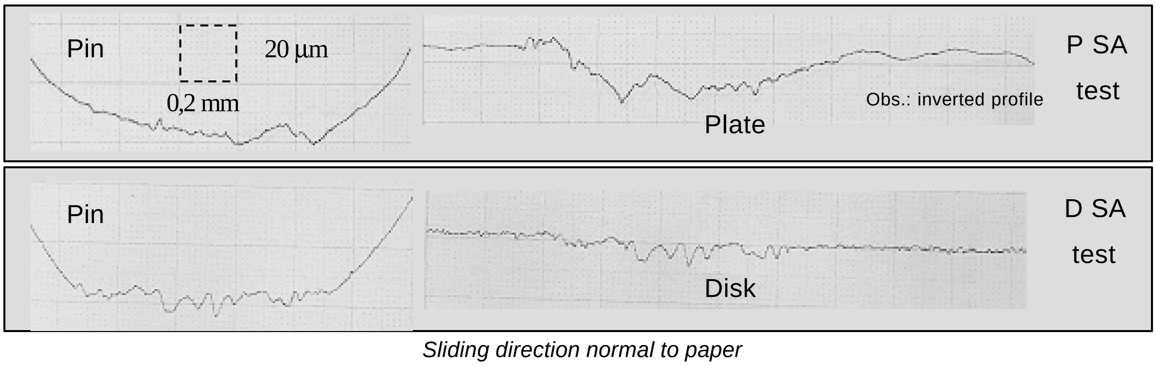

Figure 6: Worn profiles of the pins and respective counter-bodies; P SA and D SA test conditions.

Figure 7 shows details of the plastic deformation observed on the counter-bodies. Apparently, the worn surfaces are similar; however, sub-surface analyses revealed distinct degrees in deformation of the worn affected regions, seen in Fig. 8. In this Figure, material "dragging" in the sub-surface is noticed, promoted by the sliding of the pin. It is possible to see that the disk has undergone less deformation than the plate, which also presented an apparent microstructural refining.

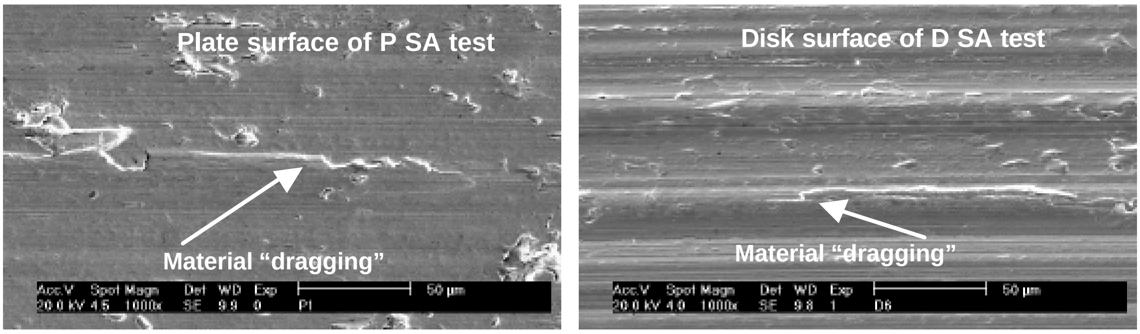

Figure 7: Microscopic appearance of the worn surfaces of the plate and the disk, P SA and D SA test conditions. Secondary electrons image.

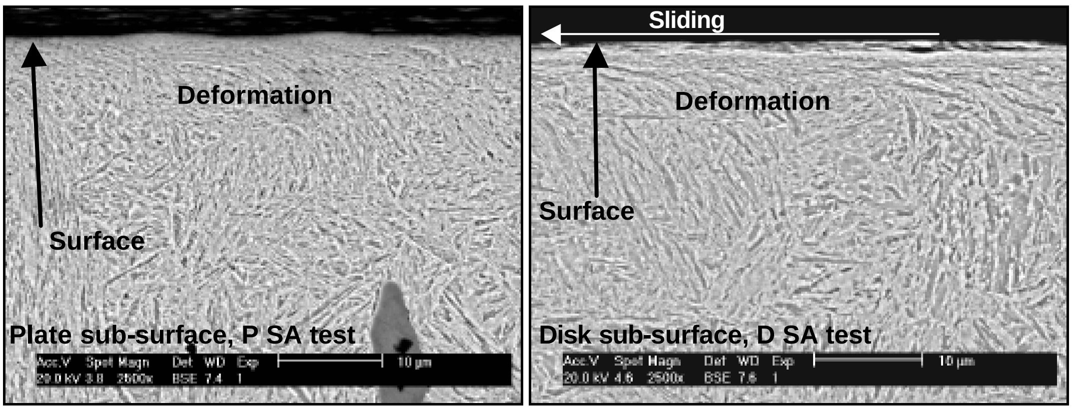

Figure 8: Microscopic observation of the worn affected sub-surface regions of the plate and the disk, P SA and D SA test conditions. Nital 3% etching, secondary electrons image.

The severe plastic deformation seen in the tested specimens indicates that the lubricant film in the contact interface was severely loaded. The use of oil with anti-wear additives is expected to result in less wear, promoted by the tribochemical reaction for protective film formation on the contacting surfaces. Figures 9 and 10 show the surface appearances of the tests with additived oil.

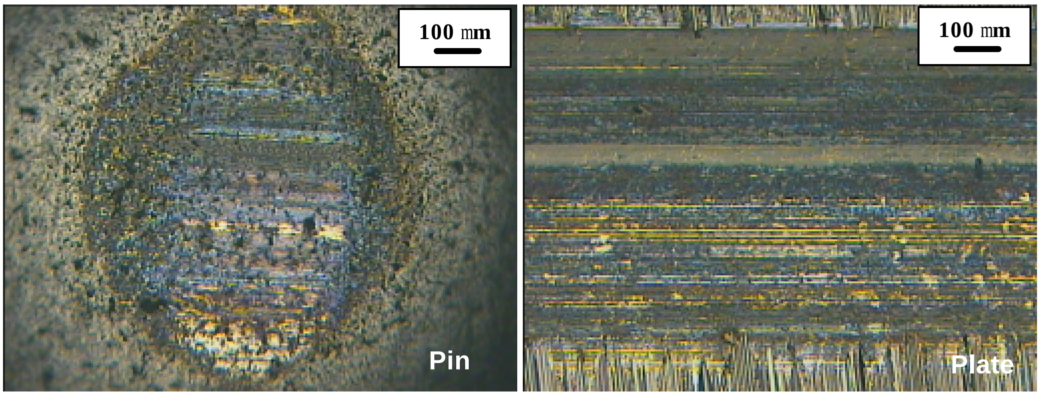

Figure 9: Microscopic appearance of the worn surfaces, P CA test.

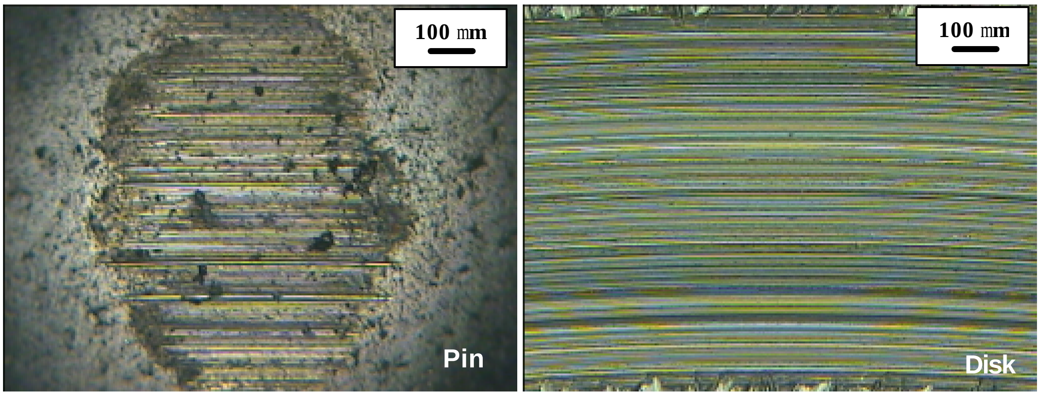

Figure 10: Microscopic appearance of the worn surfaces, D CA test.

Comparing these results to Fig. 4 and 5, it can be noticed that the plastic deformation has apparently diminished, mainly in the reciprocating test, whose worn surfaces resulted strongly darkened. Darkening was related to the presence of an adherent tribolayer on the surface.

Figure 12 shows the worn profiles of the specimens tested with additived oil. It is possible to observe that smoother surfaces were produced when additives were present in the oil. Despite the apparent suppression of the severe plastic deformation resulting from the use of additives in the oil, higher dimensional wear of the counter-body is noticed, particularly with the rotating test, when additives were present in the oil test (compare the disk surfaces of Fig. 6 and 11). In this case, the additives in the oil were favorable to promote geometric conforming by wearing the counter-body preferentially.

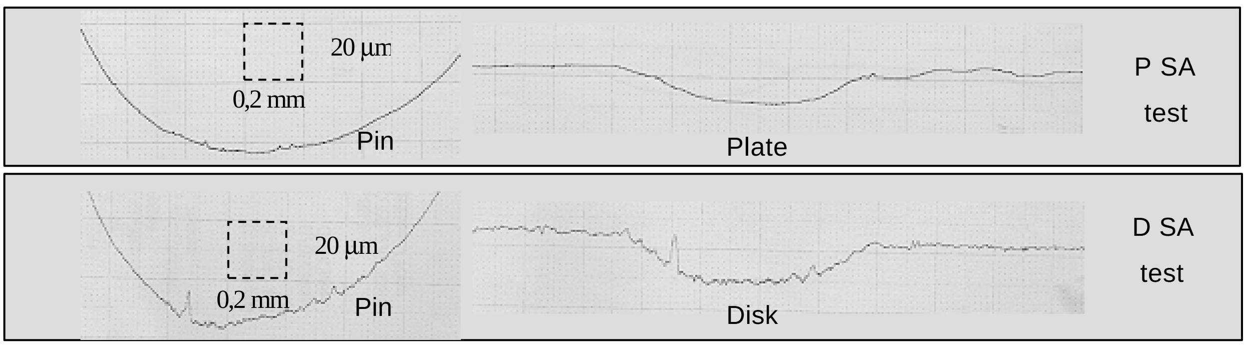

Figure 11: Worn profiles of the pins and respective counter-bodies; P CA and D CA test conditions.

The differences among the results of reciprocating and rotating tests were more evident in the tests with additived oil. Figure 12 evidences the details of the worn surfaces of the plate and the disk tested with additived oil. Morphology similar to microcrack is observed in the plate surface. In the disk, surface scratching predominates; apparent microcracking is seen only at the edges built-up by scratching. This indicates worn particle pre-forming, more evident in Fig. 13.

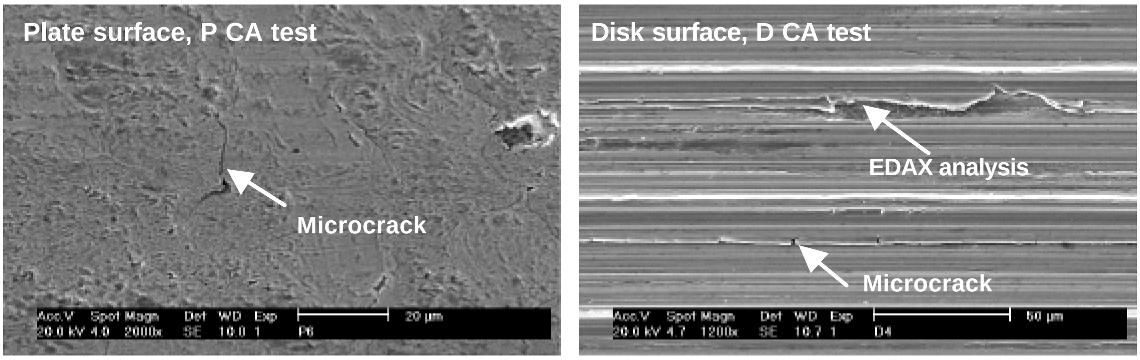

Figure 12: Microscopic appearance of the worn surfaces of the plate and the disk, P CA and D CA test conditions. Secondary electrons image.

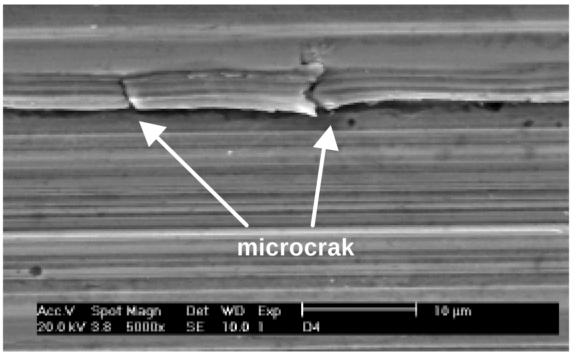

Figure 13: Microscopic appearance of the worn surfaces of the disk of D CA test. Detail of surface microcraking and apparent wear particle pre-forming. Secondary electrons image.

The chemical analyses by X-ray energy dispersive spectroscopy (EDAX) of the darkened surfaces of the pin and the plate of P CA test revealed the presence of elements from the additive of the oil. The resulting spectra are shown in Fig. 14, where P element is seen on the pin and both P and S are on the plate. The same technique was applied for the specimens of D CA test. Additive elements were evident only in the ridge of the scratches of the disk, as indicated in Fig. 12. The resulting spectrum is shown in Fig. 15.

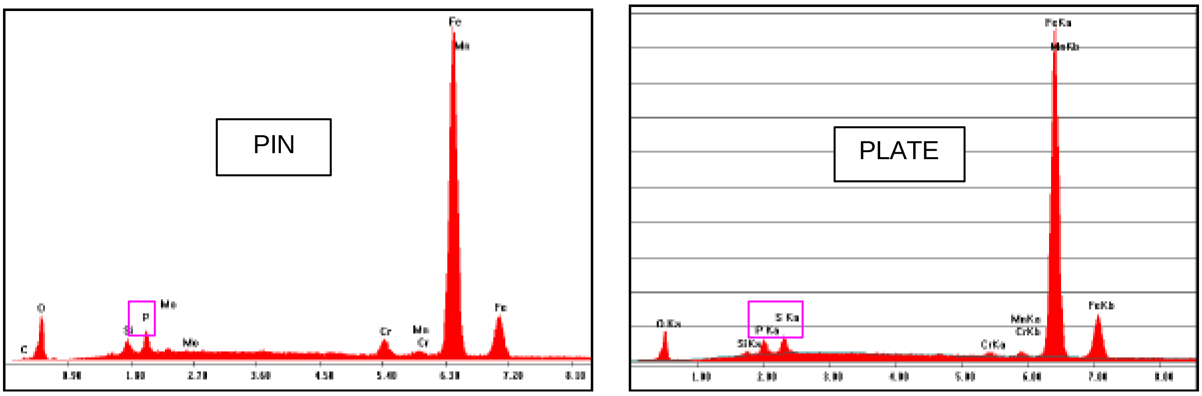

Figure 14: EDAX spectra obtained from darkened areas of the specimens tested under P CA condition.

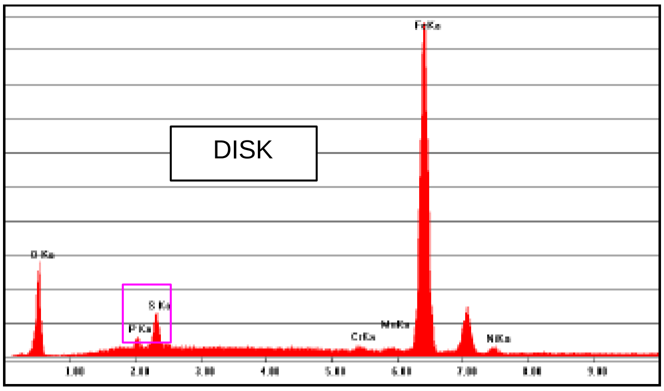

Figure 15: EDAX spectra obtained from the ridge formed on the disk worn surface, D CA test.

Microcraking at plate worn surface in Fig. 12 indicates a possible mechanism similar to surface fatigue acting in the P CA testing condition. Details of this feature were observed through analyses in the worn sub-surfaces. Figure 16 shows the wear affected sub-surface areas of the plate of P CA test and the disk of D CA test.

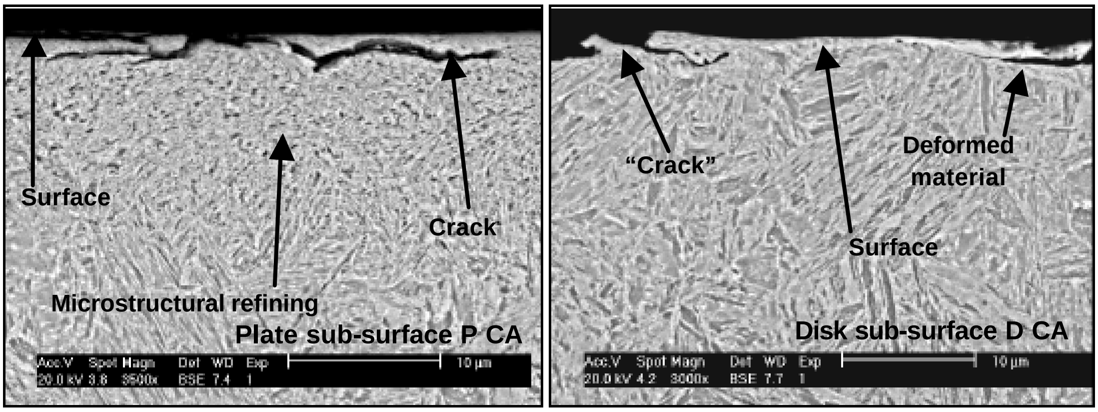

Figure 16: Microscopic observation of the worn affected sub-surface regions of the plate and the disk, P CA and D CA test conditions. Nital 3% etching, secondary electrons image.

This Figure reveals the presence of cracks in the plate sub-surface, emerging to the surface. The plate also presented microstructural refining, not evident in the disk sub-surface. Still in the disk, some morphology similar to cracks is seen; however, areas with deformed material are also observed near the surface. Comparing to the plate, it is evident that the disk had less sub-surface changes.

Another point is that the sub-surface plastic deformation (material "dragging") was suppressed in the tests with additived oil, seen by comparing Fig. 16 and Fig. 8. The cracking resulting in the additived oil tests can be related to ductility loss of the material, promoted by the chemical elements of the additive, probably by hydrogen embrittlement.

The sub-surface observations confirm the action of different wear mechanisms in the tests with reciprocating and rotating motion, mainly in the tests with additived oil. Most material changes have possibly occurred during the first cycles, in running-in step, when surface roughness was high. Without additives, the lubricant film should be strongly loaded, resulting in material "dragging", as seen in Fig. 8. The inhibition of severe wear mechanisms is credited to EP additives, through the formation of a tribofilm protecting the surfaces. It was observed that both systems had the plastic deformation reduced by the presence of additives in the oil, however, despite plastic deformation suppress, structural material modification has occurred, which was more evident in the plate than in the disk. In the rotating test, the tribofilm was not microscopically visible, but in the reciprocating tests, there was strong formation of a darkened tribolayer on the surfaces.

A hypothesis for the tribological differences seen among the tested systems, mainly in the tests with additived oil, is the difference in the oil flux motion around the contact. The linear motion is likely to favor particles to be held in the contact, as well as the tribofilm growth instead of detaching it. The first fact can contribute to wear increase and the second one, to tribochemical reaction. In this case, tribochemical reaction did not act in reducing the wear in quantitative terms, but has only suppressed severe wear mechanisms. In the rotating motion, there is probably more chance for renewing the oil in the contact during sliding due to the centrifugal action of the oil flux, therefore a compact tibolayer was more difficult to form. Figure 17 shows the debris particles flux deposited on the counter-bodies surface just after a test is finished for linear and rotating motion.

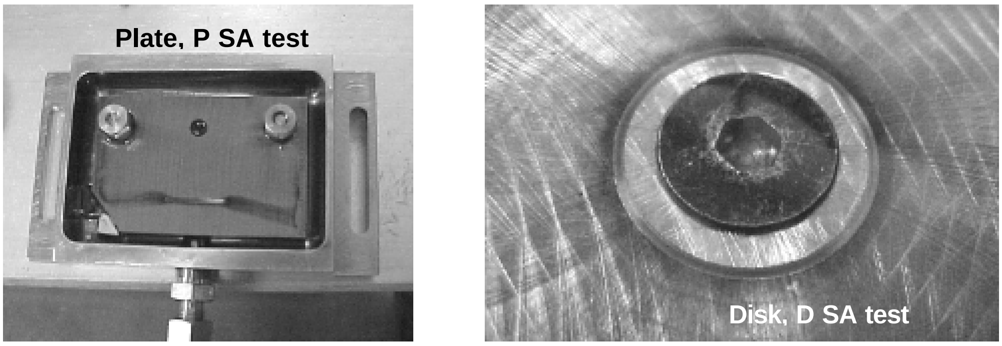

Figure 17: Worn tracks of a plate and a disk, SA tests. Observation of particles agglomeration just after the tests.

The difference in the initial roughness of the surfaces, 100 % higher for the plates, can also have contributed for the tribological differences among the systems tested with additived oil. Extreme pressure situations in the contact interface are more likely to occur for higher roughness. There are also other factors that could contribute to the tribological differences among the systems tested, as the velocity/load (V/W) rate, slightly lower for reciprocating tests. This rate is roughly proportional to the oil film thickness in fluid film lubrication. Table 2 summarizes the main characteristics to be considered in the analysis of the systems difference.

Table 2: Main differences among the tested mechanical systems.

Factor	Reciprocating	Rotating
Counter-body roughness	Transversally oriented, higher Ra (1.3 μm)	Randomly oriented, lower Ra (0.65 μm)
Surface stressing	Cyclic	Continuous
Pin cycling	100,000 cycles	50,000 cycles
Oil flux motion	Escape out the contact by the lateral edges of stroke	Escape out the contact is by centrifugal action
V/W rate [(mm/s)/N]	Lower (0.47)	Higher (0.75)
Run distance	1,600 m	3,456 m

Despite the lower pin run distance in the reciprocating test, pin wear analyses in terms of its wear affected area has revealed that the wear value was similar to that observed with rotating system (see Table 3). The values obtained of the pin wear affected area, normalized by the run distance, were higher for reciprocating tests, shown in Fig. 18.

Table 3: Mean values of pin wear affected areas, normalized by run distance.

Test code	Average area [μm^2]	Run distance [m]	Normalized area [$\mu m^2/m$]
D CA	550,000 ± 60,000	3,456	156 ± 18
D SA	760,000 ± 80,000	3,456	218 ± 20
P CA	580,000 ± 30,000	1,600	363 ± 20
P SA	730,000 ± 80,000	1,600	454 ± 50

On the other hand, observing the friction coefficient results, presented in Fig. 18, the values were lower for the rotating tests. This observation indicates that the efficiency of the lubricant oil is lower in producing low friction film in the contact with rotating system than with reciprocating one. It can be related with the oil flux motion around the contact, since the wear generated debris can remain more stable in the contact with reciprocating than with rotating motion. As mentioned by Bayer (1994), the wear debris can strongly contribute to tribolayer formation; however, it does not necessarily result in wear reduction.

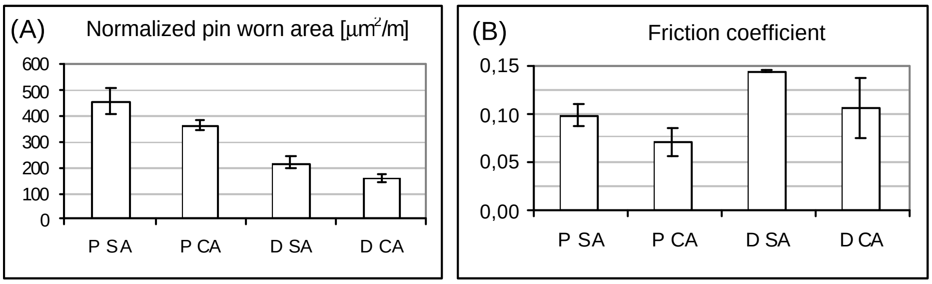

Figure 18: (A) Values of pin worn area, normalized by run distance. (B) Friction coefficient; values refer to the averages of the acquired data in the last 50 min test.

4. Conclusions

1. The wear and friction results have shown that the tribological performance of the metallic bodies was distinct for reciprocating and rotating testing configurations. Higher pin wear and lower friction coefficient were observed for reciprocating tests.
2. The mechanical system influences the contacting interface characteristics, particularly the lubricant flux and the presence of wear particles in the contact.
3. The additive presence in the oil has reduced the plastic deformation of worn surfaces, favoring surface geometrical conforming by wearing the counter-body preferentially. In the reciprocating tests, the worn surfaces showed smoothing and darkening, presenting sub-surface cracking and microstructural refining of the plates. In the rotating tests the worn surfaces were clear and uniformly scratched, with less changes in the sub-surface region of the disks.

5. Acknowledgements

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