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TRIBOLOGICAL BEHAVIOR OF NITRIDED STAINLESS STEEL AGAINST CAST IRON UNDER SEVERE TEST CONDITION

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Abstract: *This paper presents lubricated sliding wear tests results, performed in a reciprocating pin-on-plate wear test machine. The tests were performed in two test steps. The first step was run at 20 N load and 0.5 Hz oscillation frequency; the second step was run at 600 N load and 3.2 Hz oscillation frequency. Two test temperatures were used: 100 ºC and 150 ºC. The pins had two types of edge roundness: flat and 0.2 mm radius.*

The pins material was gas nitrided martensitic stainless steel and plates were made of gray cast iron, used for internal combustion engines piston rings and cylinder liners manufacturing.

After the tests, it was observed wear transition in all tests, indicated by sudden increase of friction coefficient value. It was observed material adhesion on the pins surface and changes on plate roughness. Regarding the tested plates surfaces, before the wear transition the surfaces were smoothed and after wear transition they were severely roughened.

The test temperature seemed to have no influence on the friction coefficient average value but the plastic deformed area was more visible under higher temperature pointing out a more severe wear condition.

The pin edge geometry had influence on friction and wear, and edge-rounded pins presented better trybological behavior.

Key words: *Wear, Friction coefficient, Reciprocating test, Tribology*

INTRODUCTION

Rotating or reciprocating wear bench testing machines are commonly used for wear resistant materials selection and development. Although bench test conditions are very different from real tribosystems, they are useful to provide information for phenomenological wear modeling.

Reciprocating bench tests are widely used for tribological study of internal combustion engine parts, such as piston rings sliding against cylinder liners.

Testing configuration, such as pin geometry and tribological conditions, usually is not much taken into account.

In this paper it is presented the influence of specimen geometry and testing conditions on the wear and friction coefficient.

WEAR OF LUBRICATED CONTACTS

Sliding wear can be divided in mild and severe (HIRST & LANCASTER, 1956; QUINN, 1983). Engineering systems requires mild wear conditions. Lubricated sliding system wear is strongly dependent on lubrication regime, which depends of oil viscosity, sliding velocity and loading parameters (HUTCHINGS, 1992).

In lubricated sliding systems under mild wear condition, the worn surface appearance is usually very polished. On the other hand, severe wear occurs with high wear rate and large amount of metallic debris (HUTCHINGS, 1992). The acting wear mechanisms can be surface fatigue with cracks and spalls production, abrasion with severe scratching and scuffing, which is considered as a sudden damage or failure followed by severe surface roughening and material welding. (LUDEMA, 1984).

LEE e CHENG (1991) performed transverse disk-on-disk test and observed scuffing. They associated scuffing to a sudden jump in the friction coefficient and increase in the test noise and vibration levels, and smoke emission because of lubricant flaming.

The scuffing of piston ring-cylinder liner pair of internal combustion engines leads to a components catastrophic failure when, after scuffing initiation, the engine continues to run without operating conditions modification (SCOTT et all, 1975; HAYNES, 1983). Scuffing resistant materials development is the goal of piston rings manufacturers.

Although scuffing term is intensely used, it has many controversies (LUDEMA, 1984), because it is not clearly defined and understood, regarding to the involved mechanisms, and it is recommended to avoid its use (ASM HANDBOOK, 1992).

EXPERIMENTAL

1.1. Materials

The pin material was martensitic stainless steel, with chemical composition presented in Table 1.

Table 1: Nominal chemical composition of martensitic stainless steel pin material.

Element	%
C	0.85
Si	0.40
Mn	0.30
Cr	17.0
Mo	1.00
V	0.10

The pins were machined and ground finished from wires for piston rings manufacturing to 3 mm diameter and 23 mm length, with flat edges or rounded edge with 0.2 mm radius. All pins were depassivated in salt bath; gas nitrided at 560 ºC and shot-peened for white layer removal. Figure 1 shows pin cross sections. The nitrided case thickness was about 73 micrometers.

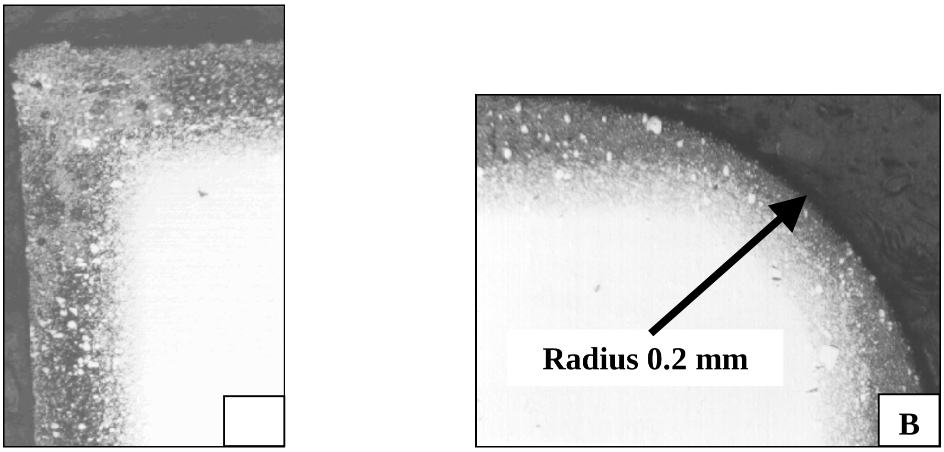


Figure 1: Optical image of gas nitrided pins, cross section, Nital 3 % etching, 200x.
(A) Flat edge; (B) Rounded edge.

Plate material was a pearlitic gray cast iron with graphites of A and B types and 4 to 7 grain sizes (Figure 2), with average hardness of 250 HB.

Figure 2: Optical image of gray cast iron plates graphites (200x).

The plates were sand cast, machined to 38 mm x 58 mm x 5 mm dimensions and ground finished perpendicular to the wear track. Table 2 shows average Ra, Rz and Rmax roughness values of finished plates.

Table 2: Average Ra, Rz and Rmax roughness values of finished plates.

Ra (micrometer)	Rz (micrometers)	Rmax (micrometers)
0.46 ± 0.10	3.7 ± 0.7	4.5 ± 0.9

For lubrication it was used commercial lubricant oil for Diesel engines, SAE 15W40, API CF.

1.2. Methods

For testing, pin-on-plate reciprocating machine with pneumatic load actuator, as presented in Figure 3, was used. This equipment allows normal load, friction force and temperature monitoring during the tests. Pin stroke on plate was of 50 mm.

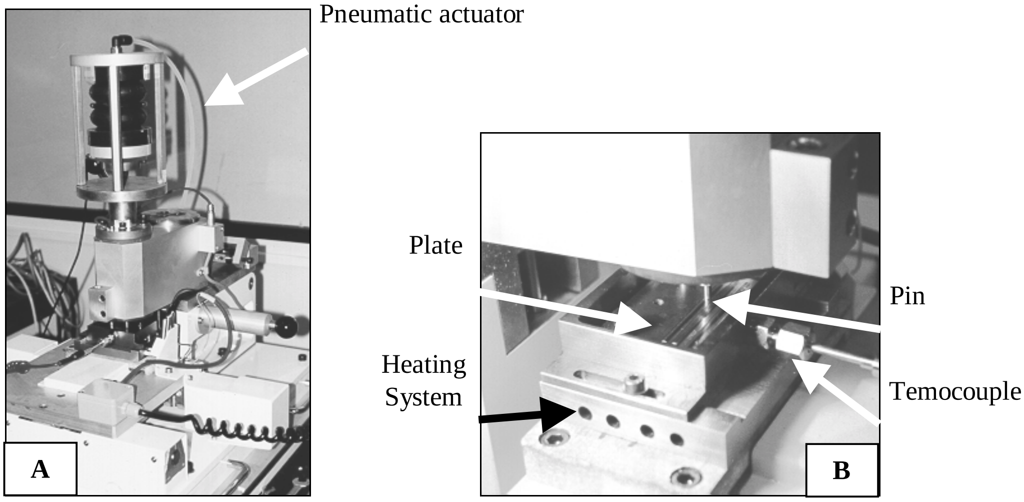


Figure 3: (A) Reciprocating pin-on-plate machine. (B) Detail close to specimens.

At the beginning of each test, the plate surface was lubricated with six oil drops, i.e., ca. 0.26 ml, uniformly distributed on the wear track region.

All tests were carried out in two steps. The first step was under 0.5 Hz oscillation frequency and 20 N normal load, to ensure enough time to heat the test up to the selected testing temperature (100 ºC or 150 ºC). The machine heating rate was 3 ºC/min.

The second step was carried up with 3.2 Hz oscillation frequency. The load was applied, at 2 N/sec rate to the final load of 600 N. Figure 4 shows the test conditions curve for a test at 150 ºC.

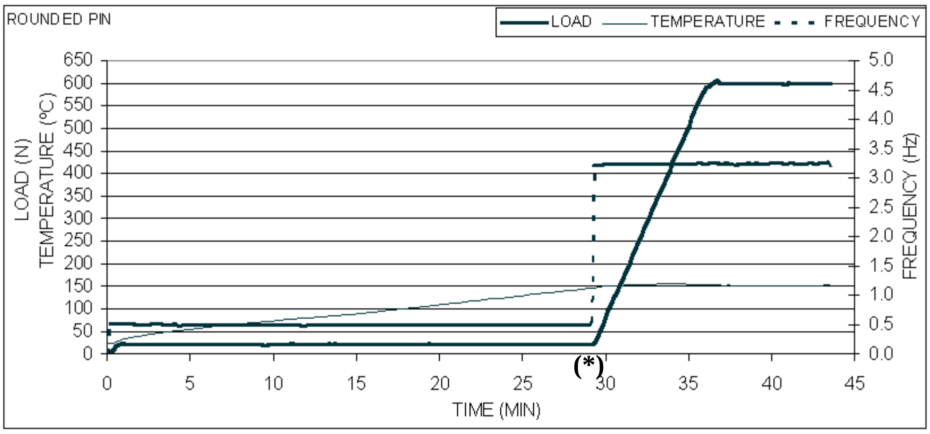
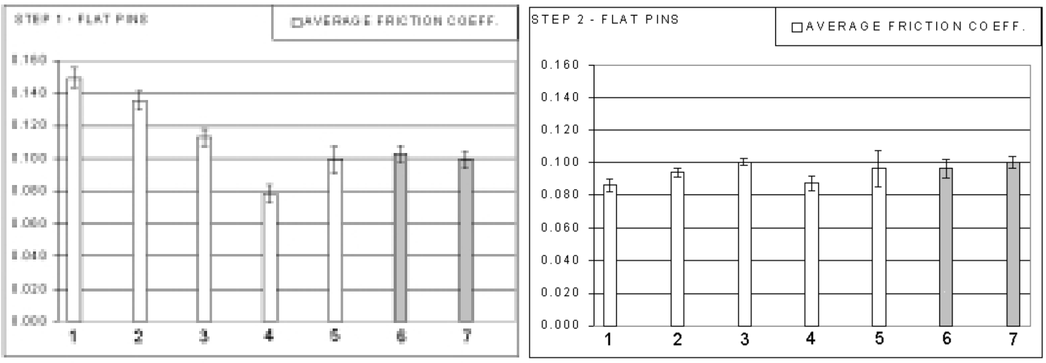


Figure 4: Testing conditions curve (load, temperature and frequency) for a rounded pin tested at 150 ºC. (*) Test step changing.

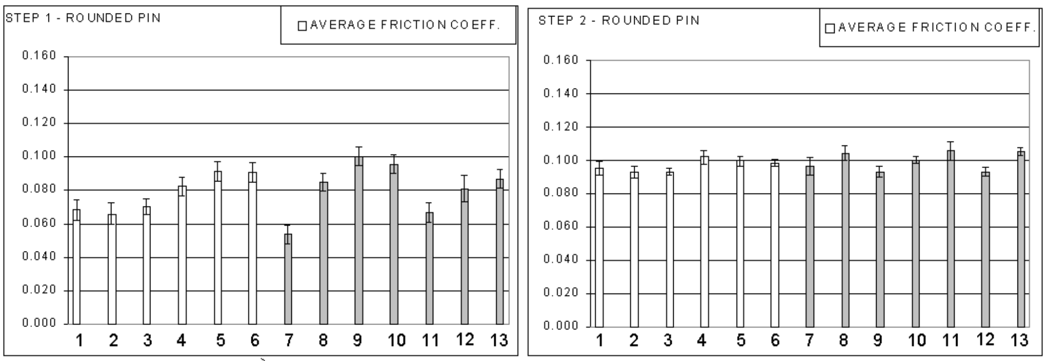
The tests were completed automatically by the computer program when a sudden rise of the friction coefficient value occurred. For tests where it could not occur, it was adopted a maximum test time of 4.8 hours.

RESULTS AND DISCUSSIONS

The average friction coefficients for all tests are presented in Figure 5 and in Table 3.



Tests with FLAT pins, nos. 1 to 7.
FIRST graph: step 1; SECOND graph: step 2. White bars: 100 ºC; shaded bars: 150 ºC



Tests with ROUNDED pins, nos. 1 to 13.
FIRST graph: step 1; SECOND graph: step 2. White bars: 100 ºC; shaded bars: 150 ºC

Figure 5: Average friction coefficient of flat and edge-rounded pins.

Table 3: Average friction coefficient of flat and edge-rounded pins.

Temperature (ºC)	Tests with flat pins		Tests with edge-rounded pins	
	Step 1	Step 2	Step 1	Step 2
100	0.12±0.03	0.093±0.006	0.078±0.011	0.097±0.004
150	0.101±0.003	0.098±0.003	0.081±0.016	0.100±0.006

From Figure 5 and Table 3, it can be observed that there were no remarkable temperature influences on the friction coefficient.

Comparing the bars between steps in Figure 5, it can be observed in general, that step 1 values (left side graphs) were more scattered than those of step 2 (right side graphs). It suggests that there were influences of the transient testing condition of step 1 on average friction coefficient values. Since lubricant viscosity is temperature dependent, and the testing temperature increased during step 1, the acting lubrication regime would have been time dependent. The low load and speed levels of step 1 could have been able to promote influence of lubrication transient behavior on friction. Moreover, at beginning of tests, plate (counter body) surface roughness was higher, thus it is reasonable that friction coefficient was more erratic at step 1. After the end of step 1, it was visually observed some brightness increase of plate surface.

Figure 6 shows a comparison of friction coefficient behavior between steps 1 and 2 of a test. It can be observed that the friction coefficient in function of time presented higher oscillation during step 1 than step 2. The low levels of load and speed of step 1 could also have been able to instigate some possible susceptibility of friction to the high roughness plate surface.

The average friction coefficient values of step 2 for flat and rounded edge pins were almost identical. On the other hand, the step 1 values of each pin geometry presented opposite behavior, if compared to step 2 values. For flat pins, the step 1 values are higher than step 2, and for rounded edge pins the step 1 values are lower. This behavior can be attributed to better lubrication provided by the pin roundness. Moreover, the flat pin can behave as cutting tools during sliding, increasing friction coefficient and wear.

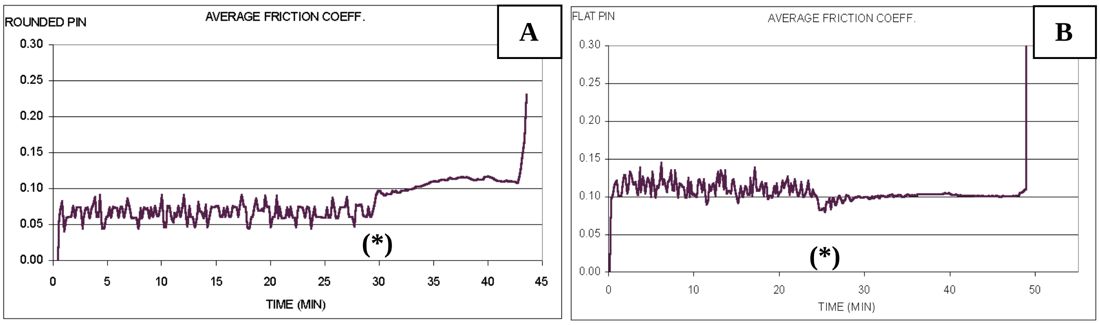


Figure 6: Friction coefficient in function of time. A: test at 150 ºC with edge-rounded pin. B: test at 100 ºC with flat pin. (*) Test step changing.

In all tests, almost at the end, it was observed a sudden increase of friction coefficient as is shown in Figure 6. It was noticed an intense noise increase and high debris production, characterizing mild to severe wear regime transition.

The wear transition of rounded pins occurred after the maximum load of 600 N. On the other hand, for flat pins, all tests except one were shutdown before 600 N load were completed.

Both friction coefficient and wear transition load results evidenced the contacting profiles geometry influence on the tribological behavior of sliding systems.

It was observed another evidence of the contacting profiles importance on engineering sliding assembly's design. The optical and scanning microscopy image of flat pin worn surface tested at a 150 ºC, presented in Figure 7(A), showed some localized plastic deformation at pin edge. Same morphology was observed on pins tested at 100 ºC. The localized deformation at pin edge indicated high stress acting at the contact edge, as demonstrated by Engel (ENGEL, 1976).

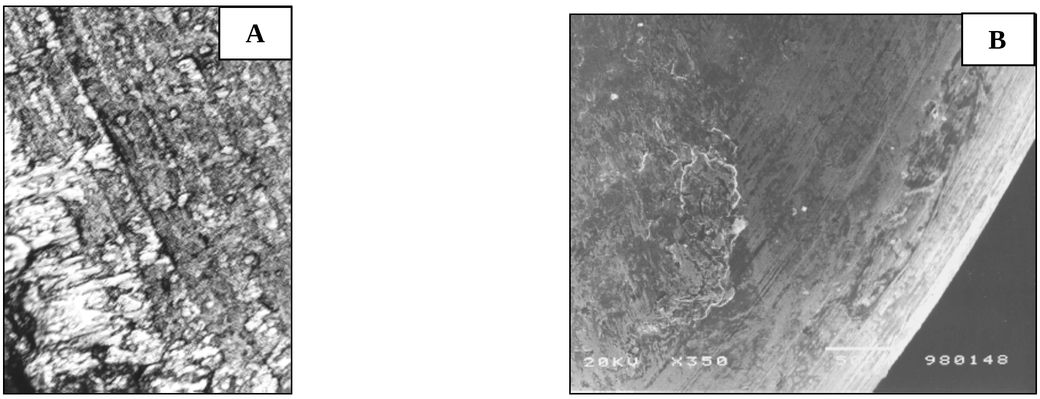
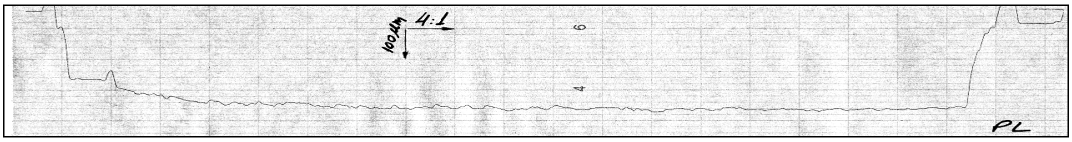


Figure 7: Pins worn surface appearances. (A) Optical image, 150 ºC, flat pin, 200x; (B) Scanning electronic microscope image, 100 ºC, edge-rounded pin, 350x.

For edge-rounded pins, shown in Figure 7(B), the plastic deformation occurred near center of specimen. The deformation could be better visualized on pins tested at the higher temperature, pointing out more severe wear condition.

Plates worn surface profiles shown in Figure 8, revealed deep ditch in wear tracks region. This ditch was formed after the wear transition, indicating catastrophic damage. It can be also observed increase in Ra, Rz and Rmax, compared to the original roughness values, before wear tests.



(A)

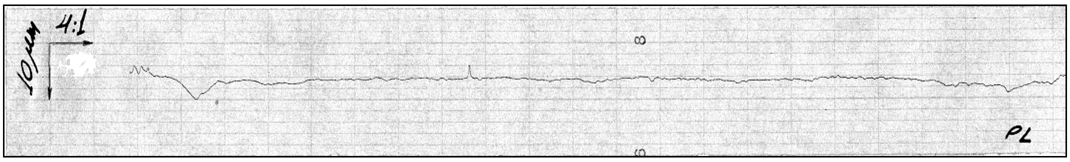
Ra: 2.27 **Rz: 14.1** **Rmax: 17.0**

(B)

Ra: 3.72 **Rz: 19.7** **Rmax: 27.1**

Figure 8: Plates wear track profiles, longitudinal direction. (A) Flat pin (150 ºC); (B) rounded edge pin (100 ºC). Roughness values in micrometers, measured in transverse direction.

Before the wear transition, it was observed smooth track without any ditches. Roughness measurements of some plates wear track, before the mild to severe wear transition occurrence, showed a high decrease in roughness parameters. Figure 9 presents a plate wear track profile and the respective roughness values after a preliminary test without wear transition occurrence.



Ra: 0.063 **Rz: 0.697** **Rmax: 0.839**

Figure 9: Plate wear track profile, longitudinal direction, after a preliminary test without wear transition occurrence. Roughness values in micrometers, measured in transverse direction.

Therefore, considering wear regimes and roughness changes at wear transition, the mild wear could be associated to a smooth sliding, generating very polished and bright surface. The previously mentioned noise change during friction coefficient increase can be related to the sudden increase of plate roughness, producing test vibration increase and noise emission. Consequently, the two wear modes (before and after wear transition) could be related to the surface roughness modification.

SUMMARY

Performing lubricated reciprocating test of stainless steel pins against gray cast iron, the mild to severe wear transition was observed.

During transition, sudden increase of friction coefficient, intense noise emission and large amount of debris accumulation were observed.

The noise emission can be associated to the trybological system vibration mode changes, due to the increase of surface roughness.

The ditch formation on the plates worn surfaces and the high final roughness values indicates a severe and catastrophic damage occurrence after wear transition.

The flat edge pins test results presented:

- Average friction coefficient of 0.10 under low or high loads;
- Material deformation localized at the pin edge;
- The wear transition at load lower than 600 N, promoting test shutdown by seizure, due to the sensibility of trybological system to the cutting edge action of pins and inefficient lubrication;

The rounded edge pins test results presented:

- Average friction coefficient of 0.08 under low load;
- Material deformation localized near center of pin tested surface;
- No testing shutdown occurred up to applied load of 600 N, pointing out good sliding behavior of trybological system.

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