24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2212
SLIDING WEAR OF LUBRICATED AISI 304 STAINLESS STEEL

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Abstract: *The use of lubricants in mechanical systems is widely known in the industry, especially in the automotive industry. The technological innovation of automobiles aiming to improve their performance and autonomy leads to develop new designs of machines, materials and types of lubricants. The automotive market demands, each day, vehicles that are faster and more powerful and, at the same time, quieter and less polluting. One of the variables involved in the quest to achieve these characteristics is the lubricant used. In many cases, the suitability of the lubricants to the new mechanical requirements leads to the use of additives capable of improving their performance at high temperatures and pressures, or simply to modify their friction characteristics. The objective of this work was to construct a wear-testing machine, pin-on-disk Tribometer, which allowed studying the wear behavior of AISI 304 stainless steel, rubbing against itself in a lubricated environment, under a relative velocity of 5.4 m/s. Tests were performed using three types of lubricants: SAE 15W40, SAE W90 and the additive Millitec-1, mixed with SAE 5W40. For each condition, three normal loads were used: 5, 10 and 25 N. In addition, a dry test was performed to serve as an initial reference. During the tests, the friction forces and the contact temperatures were monitored in real time. The wear was evaluated by measures of mass loss and the coefficient of friction, while the surface damage was accompanied by measurements of surface roughness and analysis by optical microscopy and scanning electron microscopy. The results showed that the higher frictional forces and surface damages were obtained in the dry tests, regardless of the loading condition tested. SAE W90 oil was the best set of properties, followed by SAE 15W40 and SAE 15W40 mixed with the Millitec-1 additive.*

Keywords: *sliding wear, lubricated friction, test bench, AISI 304 stainless steel, Militec-1 additive*

1. INTRODUCTION

In lubricated sliding metal systems, the presence of the lubricant in the interface promotes the reduction of both friction and wear. According to Bayer (2004), the coefficient of dry friction can vary between 0.5 and 0.1, and can decrease to a quarter of that under the influence of lubricants. The author also mentions that, in general, the reduction of the wear is more accentuated than the reduction of the friction, being placed in an order of magnitude. In any case, the degree of reduction of wear and friction is related to the geometry of the contact, the characteristics of the lubricant and, consequently, the lubrication regime involved.

As for lubrication regimes, this is a consequence of variables such as applied pressure (contact pressure) and relative velocity between bodies, as indicated by Stachowiac and Batchelor (2005). These regimes are classified into HD - hydrodynamic, EHD - elastohydrodynamic and boundary lubrication. The first corresponds to the sliding of the bodies on a film of lubricant, not leading to deformation; the second, refers to situations where, despite the film between the bodies, there is contact of their surfaces and consequent deformation; finally, the third one indicates situations in which there is no fluid film (Maru, 2003).

Hutchings (1992) states that if the contact between the surfaces is of the non-conforming type, where the contact occurs only in a line or a point, the pressures developed in the region of the contact can reach the range of GPa. In these conditions the lubrication regime will be EHD and the viscosity of the lubricant will define the best or worst friction situation between the surfaces. Viscosity is a measure of shear fluid resistance and is strongly influenced by temperature, usually decreasing with increasing it. The term viscosity index is a means of expressing this variation: the higher the index the lower the viscosity changes with temperature. Automotive oils, in general, are known to have high values of viscosity indexes favored, mainly, by the use of additives. The author also cites that viscosity varies as a function of working pressure and that mineral oils under contact pressure of 500 MPa can achieve viscosities 20,000 times greater than atmospheric pressure.

For Czichos (1992), in lubricated wear occur numerous phenomena related to surface deterioration and the generation of wear particles. And both wear and friction are strongly dependent on the lubrication regimes present, due to the particularities involved in the contact interface in each regime.

The study of the consequences of the contact between two surfaces is the subject of permanent research whose results, in general, are dependent on many variables, such as: lubrication, temperature, oxidation, relative speed and type of contact.

The purpose of this work was to analyze the wear behavior of a annealed AISI 304 stainless steel, rubbing against itself, through pin-on-disk wear tests (under non-conforming contact) using different lubrication conditions and normal loading. One of the specific objectives was to evaluate the influence of the additive Militec-1 when mixed with 5W40 automotive oil.

2. EXPERIMENTAL PROCEDURE

Sliding wear tests, pin-on-disk type, were performed using the guidelines stipulated by ASTM G99. The material used in both the disks and the pins was the annealed stainless steel AISI 304. The disks were made with 60 mm diameter by 20 mm thickness and the pins with 19 mm diameter by 20 mm height. The disk and pin surfaces were prepared by sanding (up to 3000 sanding) and then polished with diamond paste (3 µm).

A wear test machine (Tribometer) was specially designed and built for the tests, as shown schematically in Fig. 1. Its instrumentation, through electronic sensors, allows the obtaining of tangential force data in the contact region (friction force), pin temperature and rotation speed of the disk.

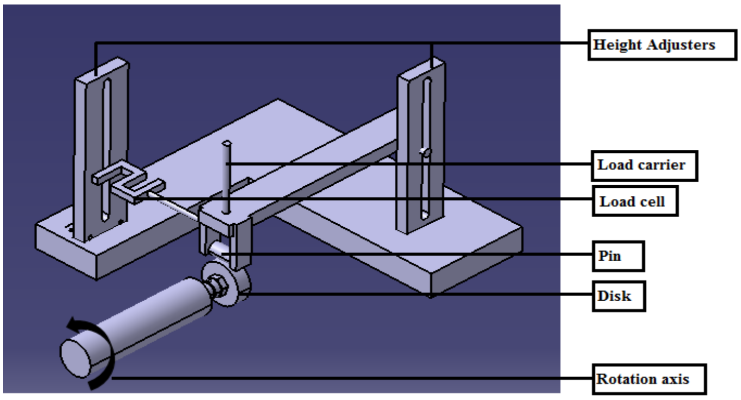
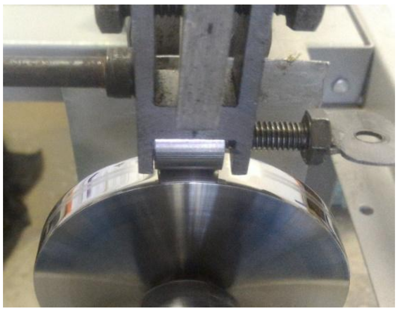
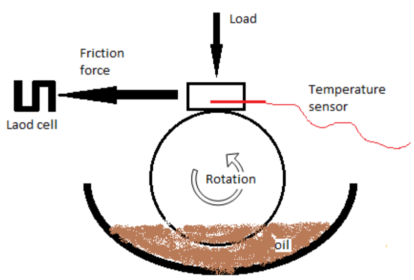


Figure 1. Simplified layout of the built-up bench

The pin-to-disk contact was established on the circumference of the disk, as shown in Fig. 2 (a); and the experimental configuration used is shown schematically in Fig. 2 (b)


(a)



(b)

Figure 2. (a) Pin-to-disk contact; (b) Schematic drawing of the experimental arrangement used.

For the sake of comparison, the tests were performed using two types of lubricants: SAE 5W40 and SAE 90, and a mixture of SAE 5W40 with Militec-1 additive (the concentration of additive used was that recommended by the manufacturer of Militec-1). The disks were partially dipped into the lubricant so that rotation of the system ensured uniform lubrication of the contact surface (Fig. 2 (b)). Dry tests were also carried out; where the pin-on-disk contact occurred without lubrication, the results of which were used as a parameter of comparison to better understand the performance of the oils in the system.

In addition to lubrication, the normal load was also considered as the test variable. Therefore, loads of 5N, 10N and 25N were used with each lubrication system, and dry; totaling, thus, 12 trials. The time of each test was 20 minutes, during which the tangential velocity of the disk was kept constant at 5.4 m/s.

During the tests, the temperature in the pin and the friction force developed in the contact were recorded and collected in real time (considering the normal force, it is possible to calculate the friction coefficient). Before each test the initial mass of each pin was measured on an analytical balance, as were the surface roughness of the pins and disks. After the tests, the mass of the pins was measured again, and wear was calculated by means of the mass loss occurred in each situation. The surface damage of the pins and disks was evaluated by means of surface roughness measurements (carried out perpendicularly to the wear marks), determination of the wear mark geometry (mark dimensions), and analysis by optical microscopy and scanning electron microscopy.

3. RESULTS AND DISCUSSION

The results showed that the highest coefficients of friction and temperatures reached by the pins were obtained in the dry tests, under all tested conditions, as shown in Fig. 3. It was also noticed that the coefficients of friction obtained during the tests are within the expected values for steel-steel pairs, with variations from 0.1 to 0.8, with and without lubrication conditions (Hutchings, 1992).

In the dry condition, the coefficient of friction increased progressively as a function of the test time and the applied load and the high friction condition present, with $\mu > 0.3$, is characteristic of a tribological system governed by surface plastic deformation mechanisms of bodies in cash (Hutchings, 1992). It is interesting to observe that the results found are in agreement with the modern view of friction, which establishes that the different friction coefficients observed in the contact between the same materials are a consequence of the influence of variables such as contact pressure, temperature and lubricants. (Maru, 2003 apud Ludema, 1988).

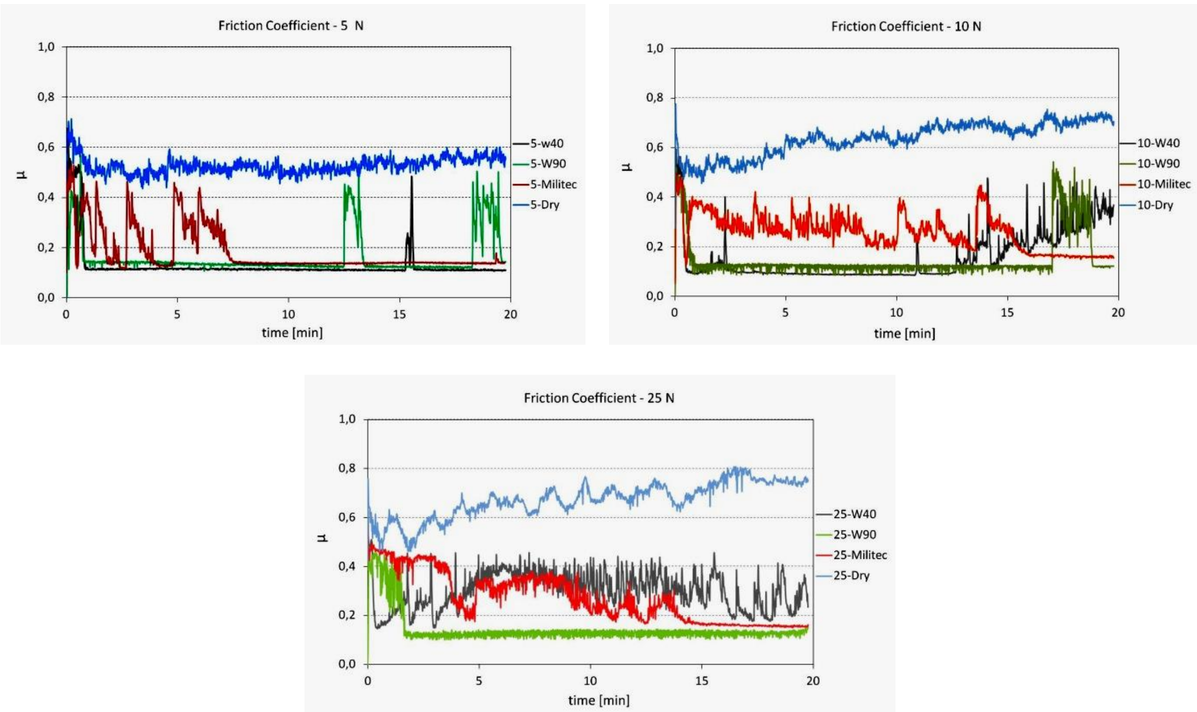


Figure 3. Friction coefficients of calculated according to the lubrication system used, the normal load applied and the test time.

The friction coefficients obtained in the lubricated systems, with values of μ lower or close to 0.3, confirm the influence of the lubrication regime on the wear surfaces. In this condition it is verified that the values of μ are smaller than those obtained in the dry tests, but unlike the previous ones their behavior is very heterogeneous depending on the type of lubricant used. In all cases, high values of μ at the beginning of the tests, corresponding to the running-in regime, are observed. However, after this period, where a stabilization of the μ values could be expected, only in the W90 oil trials does this actually occur.

In the systems using W40 and Militec, large variations of μ were observed during the tests. With the load of 5N, the system with Militec takes approximately 7 min to stabilize in $\mu = 0.14$, and remains constant until the end of the test. In the case of the W40, the system stabilizes in approximately 1 min in $\mu = 0.11$, but suffers a disturbance at 16 min.

With the load of 10N, the system with Militec practically does not stabilize, with μ fluctuating between 0.2 – 0.4, and only after 16 minutes stabilization occurs, with values of μ = 0.16. The W40 system behaved in a reverse way to Militec, remaining stable most of the time with μ = 0.12 and destabilizing at the end of the test, from minute 13.

With the load of 25 N, the system with W40 never stabilized, showing values of μ between 0.2 - 0.4. The Militec system most of the time follows the fluctuation of the W40 and stabilizes only from minute 15, in values of μ = 0.15.

The results suggest that the addition of the Militec additive to the W40 oil had no positive influence on the friction behavior of the lubricated system.

In the W90 tests, the smallest values of μ, as well as the smallest perturbations, were observed. It was noted that with the 5N and 10N charges the μ perturbations occurred sporadically after 12 min of assay.

The oscillations of the μ values, observed during the tests and coincident with vibration peaks of the tribometer, could be related to adhesive, plastic deformation and fatigue mechanisms developed during the sliding. Where, locally and temporally, the oil films that separate the two surfaces would be broken, causing the formation and breaking of joints, and/or the plastic deformations that occur in the contact would modify the geometry of the surfaces. This finding becomes more evident as the normal load is increased; the most affected being the Militec system, followed by the W40 and almost imperceptible in the W90. These disturbances disappear when the lubricating film is restored or the plastic deformations settle to the surface or debris is removed by fatigue mechanisms.

The temperature values, measured on the pins during the tests, follow the same trend observed in the friction values (Fig. 3), noting that the higher temperatures were observed in the dry tests, as shown in Fig. 4. The temperature showed to be related to the energy transformation associated with the friction force in each test (Maru, 2003 apud Bayer, 1994), since the lower the coefficient of friction, the lower the rate of growth of the temperature. It was also verified that oscillations in the temperature values coincide with the moments where friction disturbances occurred.

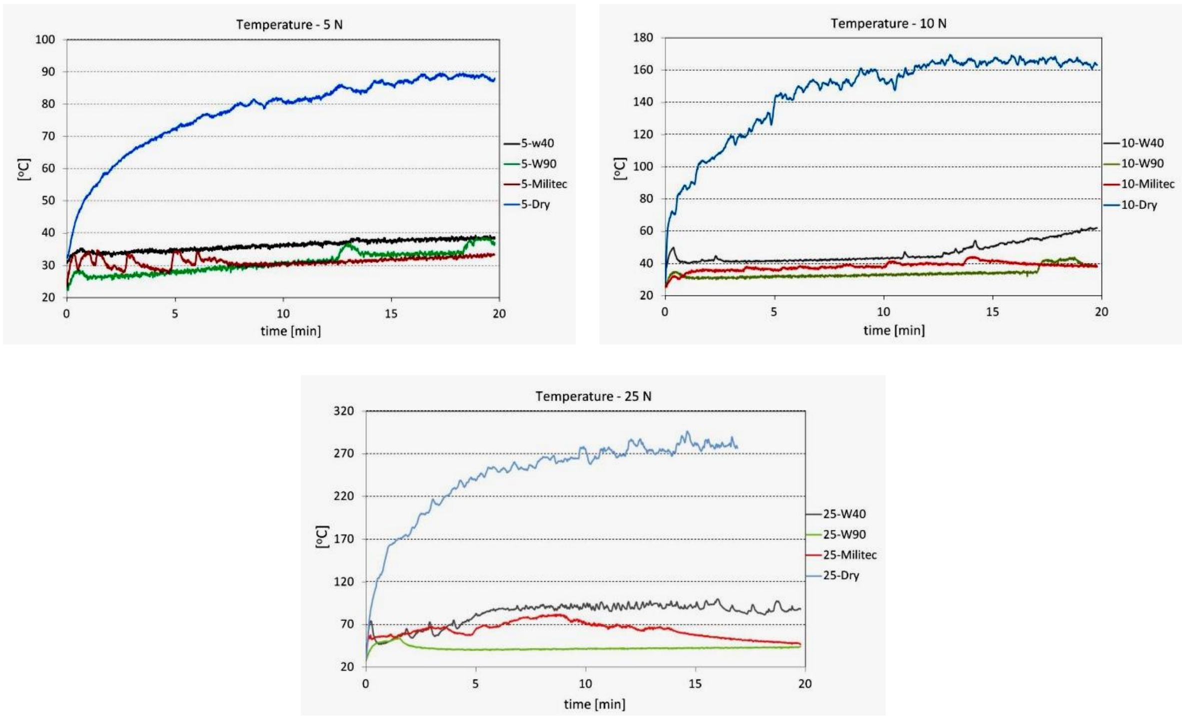


Figure 4. Temperature values measured according to the lubrication system used, the normal load applied and the test time.

The wear of the pins, determined by the loss of mass suffered during the tests, is shown in Fig. 5. Note that wear is proportional to the load applied and change in different lubrication systems. As predicted, the greatest wear occurred in the dry tests, being approximately 10 times greater than those obtained with the lubricated tests. It is also verified that the mass loss values are related to the friction values and their oscillations shown in Fig. 3.

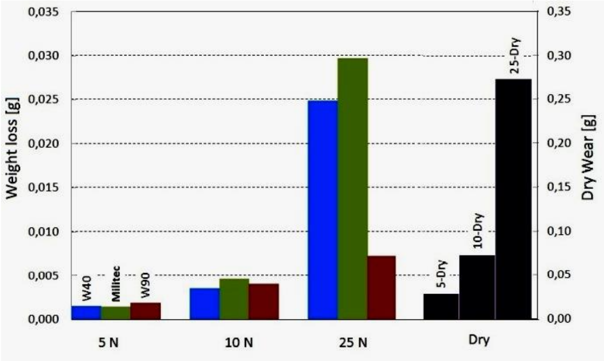


Figure 5. Mass loss of pins measured after wear tests.

With the load of 5N, the friction values and the oscillations were very similar in the three lubricated systems, which also caused a very similar loss of mass between them. However, as the load increased a clear deference of behavior between these systems began to be noticed. With the load of 10 N the friction and its oscillations were similar in the systems W40 and W90, which caused a similar loss of mass between the two, while the Militec system presented the highest coefficients of friction as well as its greater oscillations, which also promoted the greatest measured losses. This trend holds when the load was 25N.

The wear results show that, in general, the system with W90 is the one that presents the best set of properties under any conditions. It is also confirmed that the use of the Militec additive under the test conditions does not improve the performance characteristics of the W40 oil, on the contrary, it diminishes them.

Figure 6 shows the average roughness values "Ra" measured on the pins and disks, before and after the wear tests, as a function of the normal load applied and the lubrication system used. The initial roughness of both the pins and the disks was 0.05 μm due to their polishing condition. In general, it is noted that the dry tested surfaces were those with the highest roughness values. It is also verified that for any loading condition the samples tested with the W90 system exhibited the lowest levels of roughness when compared to the other three lubrication conditions. Additionally, the pins tested with W90 presented roughness values very similar to each other, with values close to 0.75 μm. In the disks the situation was very similar to values close to 0.4 μm, regardless of the load used. These results corroborate the aforementioned best friction and wear performance for the W90 system.

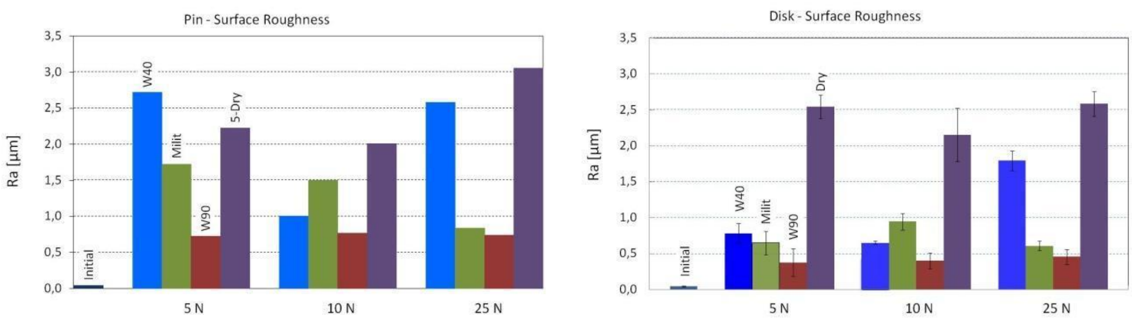


Figure 6. Average "Ra" Roughness of the Disks and Pins.

Figure 7 shows evidence of surface damage occurring on disk surfaces as a function of the applied load and the type of lubricant used. It can be observed that the tracks of wear of the dry-tested disks showed signs of severe adhesion (scuffing), of generalized plastic deformation and removal of material by micro fatigue (darker places in the photographs), which in turn caused the greatest frictional force and higher levels of surface roughness. The track width is larger than those in the lubricated systems, corroborating the larger mass losses observed in Fig. 5, and the heterogeneity of the track surface was responsible for the occurrence of vibrations in the Tribometer during the tests, which generated the small oscillations in the friction coefficient reading, shown in Fig. 3.

The surfaces of the W40 tested disks show the same signals observed in the dry tests, but with much less intensity, as evidenced by the roughness and mass loss levels. It is also noted that as the load increases, the surface damage becomes increasingly severe, which explains the large oscillations in the coefficients of friction seen previously.

In the disks tested with Militec, besides the signs of adhesion, plastic deformation and micro-fatigue, we also note the formation of grooves in the wear track, for all loading conditions. This fact confirms the oscillations recorded in the friction coefficients, the largest mass losses measured and the high levels of roughness measured.

The wear trails of W90 tested disks are the most homogeneous of all. Although signs of adhesion, plastic deformation and micro-fatigue are evident, they are less pronounced and more homogeneously distributed; which resulted in lower levels of roughness and loss of mass.

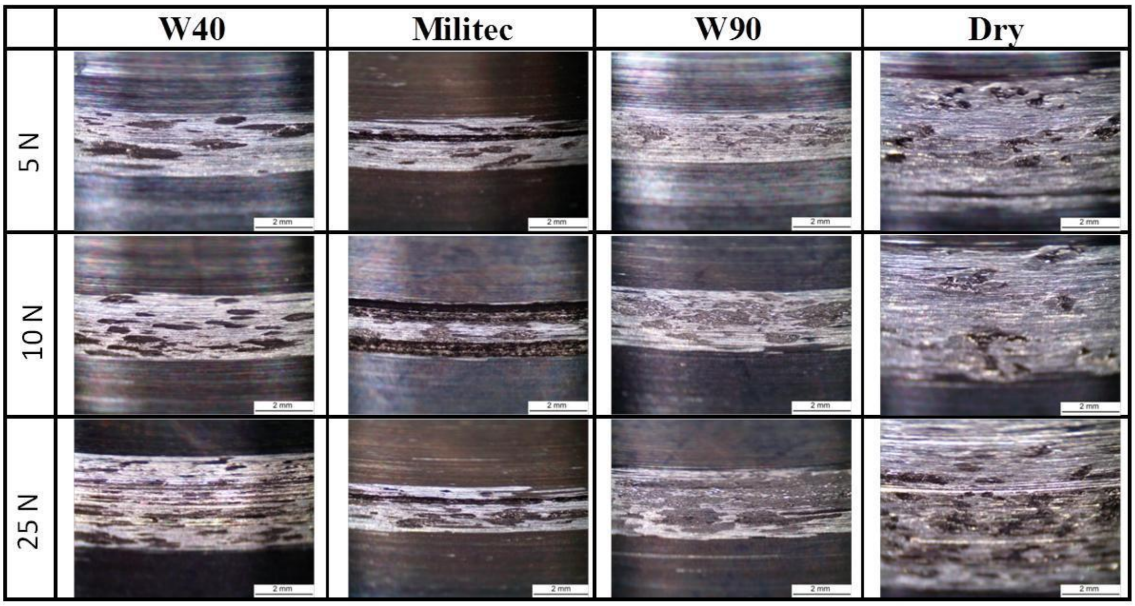


Figure 7. Surface damage on the tested disks

The surface damage of the pins is shown in Fig. 8. The size of each of the wear marks is directly related to the value of the measured mass loss: larger marks indicate larger mass losses. The photographs also show signs of generalized plastic deformation and fatigue material fracture (especially on the edges of the marks). In addition, there is evidence of transferred films, such as that observed in the W40-5 N (darker region) assay.

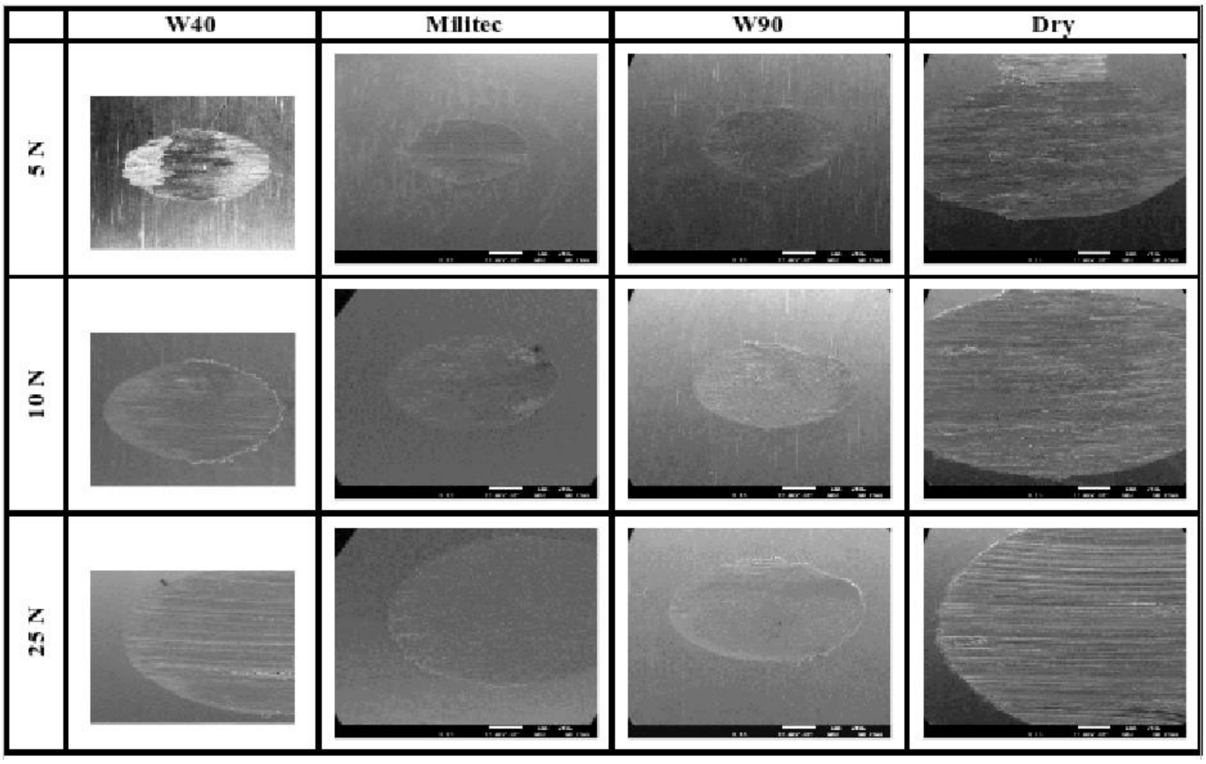


Figure 8. Surface damage on pins.

4. CONCLUSION

The tests performed in this work, in a pin-disk sliding condition, showed that the AISI 304 steel suffered the greatest wear and friction when tested dry, reaching friction coefficient values higher than 0.6.

When lubricated, the system responded in a way to offer friction and wear much more discreet, reaching values in the range of 0.1 to 0.2 friction coefficients and loss of mass ten times lower than in the dry condition.

Other factors influenced by lubrication are the temperature of the pin during the test and the surface roughness of bodies, pin and diskafter wear. Both were much higher when the lubricant was absent.

As for the action of the lubricants, when compared to each other, it was concluded that, for the conditions analyzed, the W90 obtained the best friction and wear results. Militec mixed with W40 did not improve the performance of this oil, if we compare with the results of the pure W40, which indicates that its use for the conditions tested is not adequate.

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