PARAMETERS AND PROPRIETIES INFLUENCE STUDY IN WEAR BEHAVIOUR OF A CAST STEEL DIN 16MnCr5 HELICAL GEAR

ESTUDO DE PARÂMETROS E PROPRIEDADES INFLUENTES NO COMPORTAMENTO AO DESGASTE DE UMA ENGRENAGEM HELICOIDAL DE AÇO VAZADO DIN 16MnCr5

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ABSTRACT

This work is based on the study of wear behaviour of a DIN 16MnCr5 steel pair of helical gears. Vickers micro hardness tests were carried out and an in-depth study of two zones of the material in question was studied: hardness analysis of the material composing the gear body and analysis of the hardness of the teeth in the area of head of the tooth and study of the hardness along the profile of the tooth. Finally, wear tests were carried out on the material and its behavior on dry and lubricated wear was evaluated using a pin-on-disc test machine. Parameters as friction forces, friction coefficients, volume loss of material and temperatures in function of applied forces are determinate for different tests.

***Keywords*:** Gears; Hardness; Friction forces; Friction Coefficients; Pin-on-disc Testing; Wear; Steel DIN 16MnCr5

RESUMO

O presente artigo estuda o comportamento ao desgaste de uma engrenagem helicoidal de aço vazado DIN 16MnCr5. É apresentado o procedimento experimental de corte e preparação das amostras a partir de uma engrenagem helicoidal. Foi estudado o comportamento em serviço através de ensaios laboratoriais de desgaste do material com o objetivo de caracterizar o seu desgaste a seco e com lubrificante usado com recurso a uma máquina de testes pin-on-disc. Sendo a dureza uma propriedade relevante no comportamento ao desgaste, este trabalho inclui também o estudo de dureza do material que compõe o corpo da engrenagem e os dentes na zona de contacto e a análise da dureza ao longo do perfil do dente. Parâmetros como coeficientes de fricção, forças de fricção, perda de volume e temperaturas em função das forças aplicada são determinados para as diferentes experiências.

1. INTRODUCTION

Gear transmissions play a key role in modern technology, as they transfer both power and motion with high efficiency. The interaction between gear teeth in a transmission may be affected by a wear in a negative fashion causing non-uniform gearing rate, decreasing efficiency and severe tooth failure (Flodin & Andersson, 1997).

The authors Hohn & Michaelis describe wear as a continuous failure under a thin separating film conditions, typically at slow pitch line velocities, where interaction between asperities may occur (Höhn & Michaelis, 2004).

Onishchenko label two types of teeth wear that can happen (i) low intensity wear, or normal wear, and (ii) high intensity wear, that appears with scuffing. The same author defines normal wear as a process of gradual change in size due to friction, and it's also characterized by the removal of particles of tooth material from the contact surface. Scuffing is the damage caused by the solid-phase welding between surfaces in relative motion, which is accompanied by the transfer of material from one surface to another (Onishchenko, 2015).

The most existing scuffing test consists on a moving surface is rubbed against a stationary one, at a fixed sliding speed, and the load at which scuffing occurs is determined (Ingram, Hamer, & Spikes, 2015).

This work aimed to study the wear behaviour of the DIN 16MnCr5 steel pair of helical gears (Fig 1), considering the service conditions to which they were subjected. Such conditions were: an input power to the gear motor of 5.5kW at 1500rpm, a gear ratio of 27.88 and a torque at the output shaft of 800Nm at 50rpm.

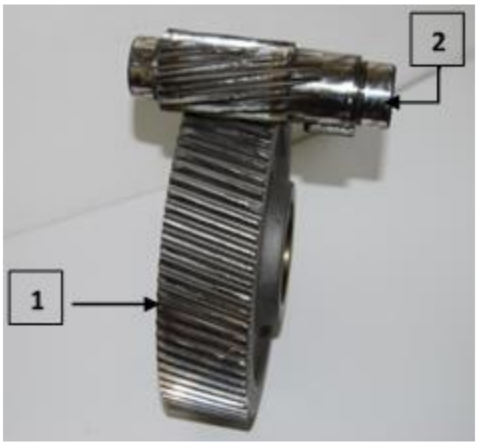

Fig 1 - Set of gears studied: (1) Helical gear; (2) pinion shaft

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The manufacturing material of the both components is DIN 16MnCr5 steel. Its chemical composition is mentioned in the table 1 (DIN EN 10084, 2008).

Water-jet cut was used to obtain test samples from the helical gear (fig 2 a)). A AutoCAD Drawing Interchange Format file was created in SolidWorks 2016 to make the two needed cuts: circular samples with 25mm diameter each were cut from the body of the gear and two teeth zones were obtained from the outer side of the gear (fig 2 b)).

Table 1 - Chemical composition of DIN 16MnCr5 steel (DIN EN 10084, 2008)

Elements	***C***	***Si***	***Mn***	***P***	***S***	***Cr***
% by mass	0.14 – 0.19	0.40	1.00 – 1.30	0.025	≤0.035	0.80 – 1.10

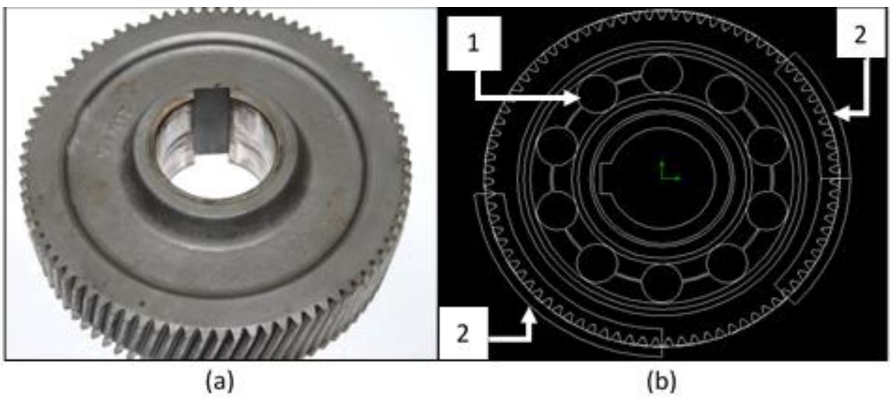

Fig 2 - (a) Helical gear; (b) positions of the cuts that were made to the gear: (1) 25mm diameter samples; (2) two sections of teeth (Mousinho, 2017)

It is possible to notice in the figure 3 a) and b) the samples cut from the body of the gear and the two sections of the teeth, respectively.

From the “cylinder crown” presented in fig 3 b), all cylinders were numbered from A to J. Cylinders B and C were a used to make the Vickers micro indentation test in the body of the gear and they were cut in 4 equal pieces of 10mm, making use of an automatic blade (Fig 4).

For the gear teeth, a section of one of the samples was cut with a grinding wheel. In the figure 5 it is shown the location of the teeth A, B and C.

2.1 Vickers micro hardness tests

The experimental procedure used in Vickers micro hardness tests followed the ASTM E384 – 16: Standard Test Method for Microindentation Hardness of Materials standard (ASTM E384-16, 2016).

The parameters used in this test were: 500gf test load, 0,3mm space between indentations and 10 seconds test duration. The specimens’ preparation for metallographic evaluation followed the ASTM E3 – 95: Standard Practice for Preparation of Metallographic Specimens standard (ASTM E3-95, 2016), and consisted in the three following steps: Specimens from

Fig 3 - (a) Samples obtained from the inner part of the helical gear; (b) teeth samples obtained for analysis

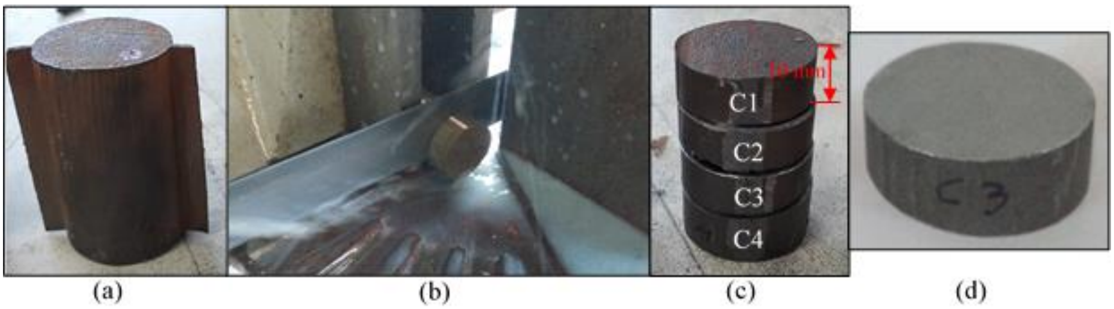

Fig 4 - Sets taken for specimens cutting for Vickers micro indentations tests in the body of the gear: (a) initial C cylinder; (b) cylinder cut using an automatic blade; (c) C cylinder cut in 4 equal parts; (d) final C3 specimen without surface preparation

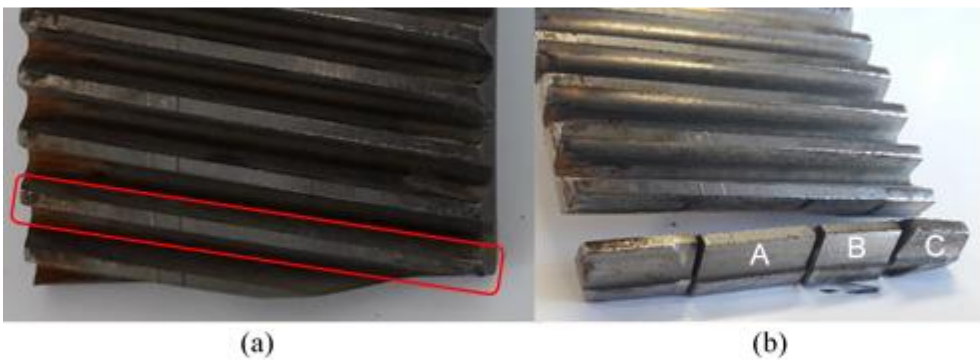

Fig 5 – Specimens cutting for teeth analysis: (a) Section of the gear teeth choose for analysis; (b) teeth A, B and C cut with a grinding wheel the body of the gear and teeth were mounted in plastic recipients with a mixture of epoxy resin. Then specimens were subjected to surface preparation: first phase was manual grinding with sequence of papers being 80, 120, 240, 360, 400, 600, 1200 and 2500; second phase consisted in polishing using a special metallographic cloth and 1μm diamond paste.

Software Minitab was used to verify if the data acquired followed a normal distribution, as required, by making probability plots using the Anderson-Darling test, in which the p-value must be equal or higher than the confidence value α of 0,05. Ten indentations were made, in each sample, for statistical treatment.

2.2 Wear tests

The wear tests were done using a pin-on-disc tribometer and the experimental procedure followed was based on the ASTM G99 – 95a: Standard test method for wear testing with pin-on-disc apparatus standard (ASTM G99-95a, 2000).

Pin-on-disc tests are widely used to evaluate the tribological performance of metal-to-metal sliding contact, in a laboratorial scale. The main characteristics assessed are friction and wear (Bortoleto et al., 2013).

The pin-on-disc tribometer is shown in 6. It consists in a pin (1), that is hold on the lever (2), in which a specimen, that is still in the support (3), is rotating against it. The load applied is putted on the support (4) and the data obtained by the load cell (5) are read in the data acquisition system (6). There is as well a counter weight (7) to adjust the height between the pin (1) and specimen surface. For the environmental control, this tribometer also has a box to seal the air, in which there is a hole for a tube (8) to debit inert gas, which was argon in this case.

The pin-on-disc tests parameters used were loads of 16,93N, 90,84N, 34,35N, 41,14N and 82,75N, rotation speed of 350rpm, argon gas debiting 5 litres per minute and tests period of 40 minutes. The load cell and thermocouple were properly calibrated.

The surface preparation of the specimens was done using a grinding machine, due to ASTM G99 standard require that the surface roughness must be less than 0,8μm (ASTM G99-95a, 2000). After the surface preparation, all the specimens were measured in three directions for surface roughness examination with a mobile roughness measuring instrument Mahr MarSurf PS10.

For the pin specimens, cylinders were processed in a turning machine making them with 5mm diameter. The pin specimens were rounded in the tip with grinding papers and a grinding wheel. A hole of 1,6mm was made at 5mm from the tip for placing the thermocouple, enabling the temperature reading in a zone close to the contact area.

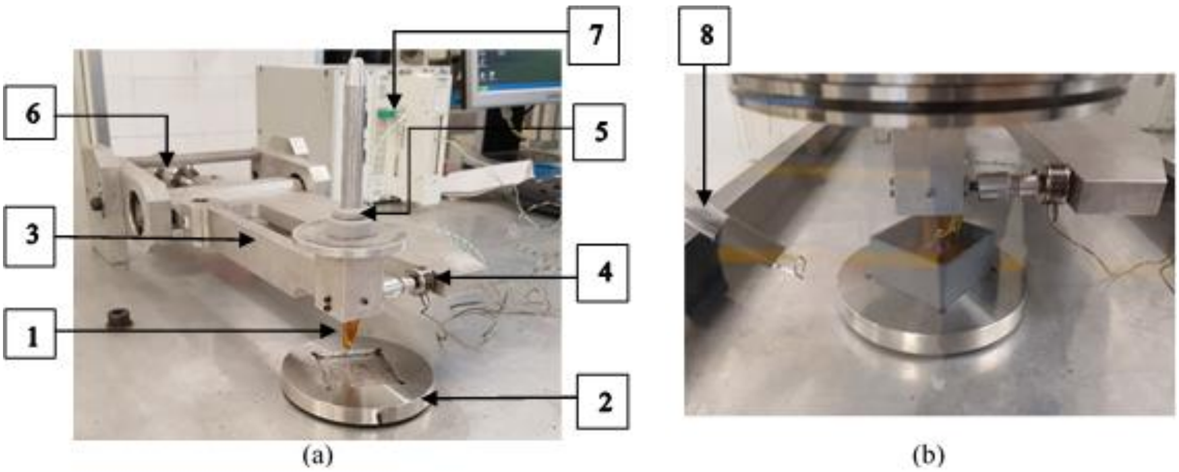

Fig 6 - Pin-on-disc tribometer: (a) 1 - pin with thermocouple, 2- lever, 3 - specimen support, 4 – weight support; 5 - load cell, 6 - data acquisition and 7 - counter weight; (b) 8 - inert gas exit tube

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Vickers micro hardness test

In fig 7 it is shown an example of the area of specimens from the gear body that were tested. All tests were performed in the positive direction of the y axil. The result for the micro hardness Vickers tests performed in the body of the helical gear was 294±3 HV.

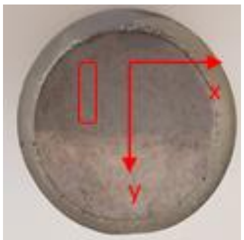

Fig 7- Identification of the area tested in the specimen B2

For the evaluation of the gear teeth, two areas from the teeth were tested: the contact zone between teeth and the profile of the teeth. It is shown in fig 8 an example of the zone where the testes were performed in the mentioned teeth. All the tests were taken in the positive x axil. The results obtained, from the area of the contact zone, of micro hardness was 699±1,2HV.

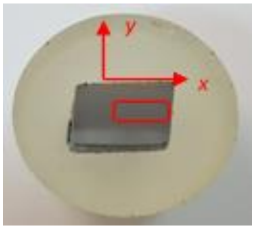

Fig 8 - Identification of the area tested in the tooth B

The third tests performed aimed to evaluate the variation of the hardness along the profile of the teeth. In figure 9 is shown the graphic of the variation of the hardness in relation the increase of the distance to the top of the teeth F as example. From the analysis made in 6 profiles teeth, it was observed that the micro hardness decrease approximately 200HV along the 5 mm of the teeth profile.

3.2 Wear tests

The first test (Test-1) performed consisted in applying a 41,14N load, for 50 minutes, with stops each 10 minutes, to weight both samples and pin. The objective of this test was to estimate the rate volume losses for both sample and pin, that are given by the equations presented in Figure 10, in which ΔV_a is the volume loss of the specimen [mm^3], ΔV_p is the volume loss in the pin [mm^3] and t is the measure instant time [minutes].

For the second dry test performed (Test-2) the objective was to evaluate the behaviour of the material when subjected to four different loads (16,83N, 30,84N, 34,35N and 41,14N). In Figure 11 it is presented the plot with the results from Test-2 and the equations and represent the exponential relations between the volume loss in both specimen (ΔV_a) and pin (ΔV_p) and the applied load F_N.

In the figures 12 to 14 are presented graphics that relate the variation of the friction force, friction coefficient and temperature near the contact zone with the

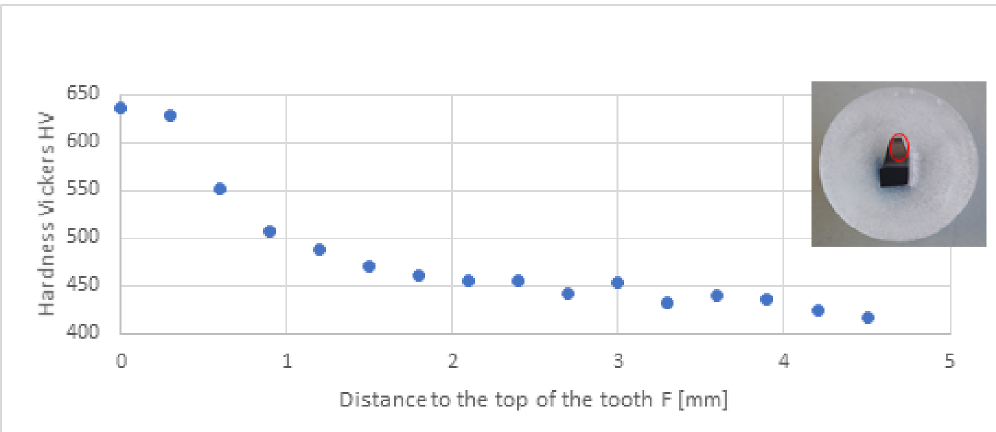

Fig 9 - Variation of the Vickers' hardness in relation to the increase of the distance to the top of the tooth F

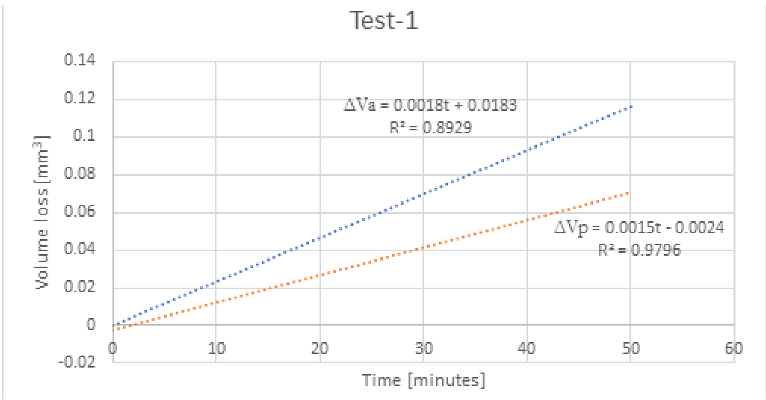

Fig 10 - Volume losses in specimen and pin, with applied load of 41,14N, for 50 minutes (Test-1)

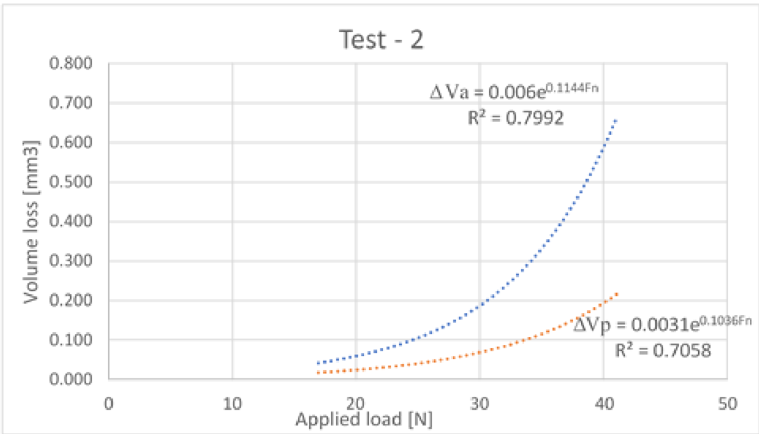

Fig 11 - Volume loss of specimen and pin in relation to the applied load (Test-2)

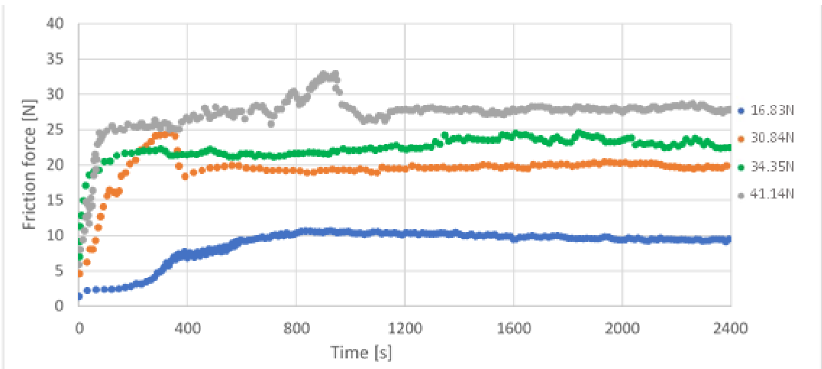

Fig 12 - Friction force registered in relation to different applied loads (Test-2)

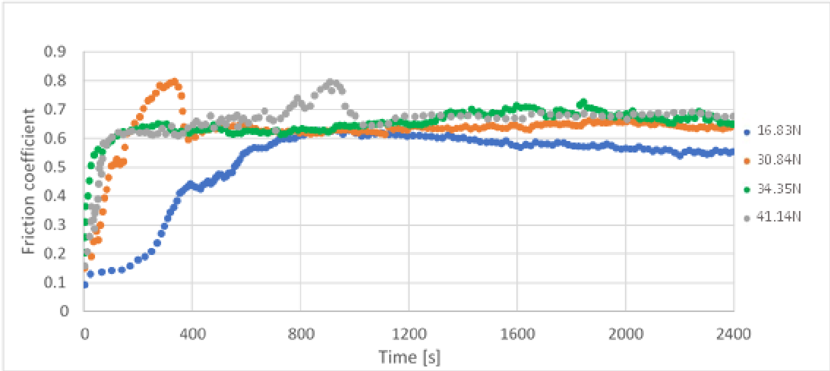

Fig 13 - Friction coefficient registered in relation to different applied loads (Test-2)

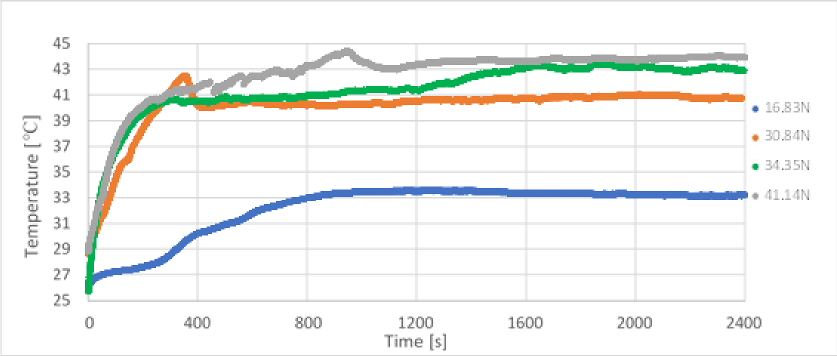

Fig 14 - Temperature registered in zone close to the contact area in relation to different applied loads (Test-2)

different applied forces (16,83N, 30,84N, 34,35N and 41,14N). It is notice the increase of the variables during the first 300 seconds, probably due to the penetration of the tip of the pin in the sample. After, the values tend to be constant, despite some punctual variations expected.

Wear tests with used lubricant were performed (Test-3). In Figures 15 to 17 are presented graphics that relate the variation in time of the average friction coefficient, average friction force and average temperature near the contact zone for the applied force of 82.75N. The biggest value obtained of volume losses for the specimens and pin, on the tests performed with used lubricant was 0.026 mm^3.

4. CONCLUSIONS

In the body of the helical gear, the average Vickers hardness value obtained was 294±3HV, with a value of 648±0.98HV

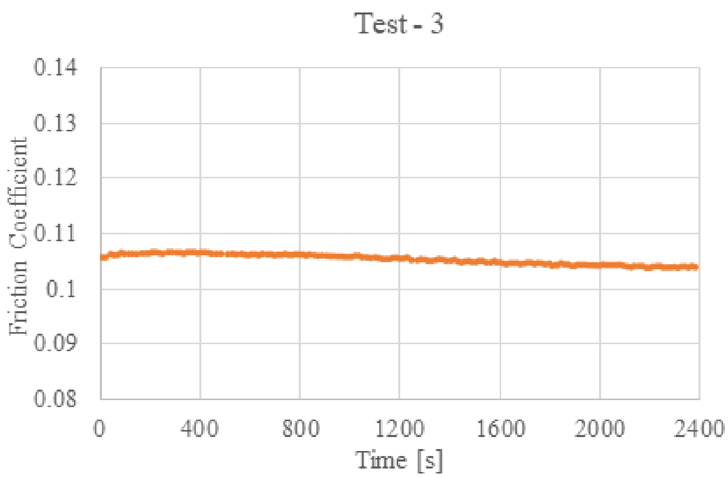

Fig 15 – Average friction coefficient obtained in wear used lubricant tests (Test-3)

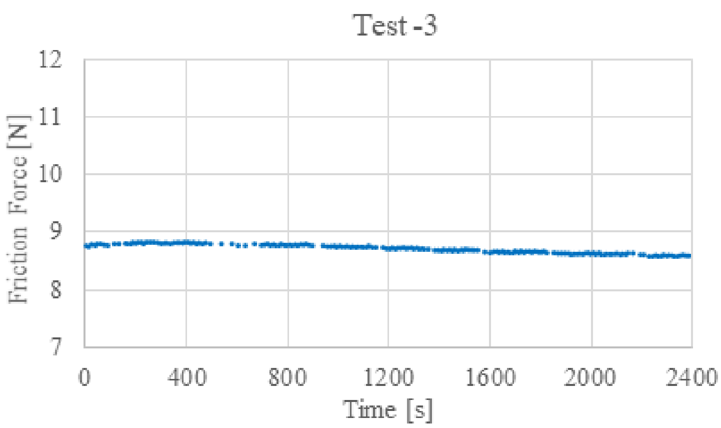

Fig 16 – Average friction force obtained in wear used lubricant tests (Test-3)

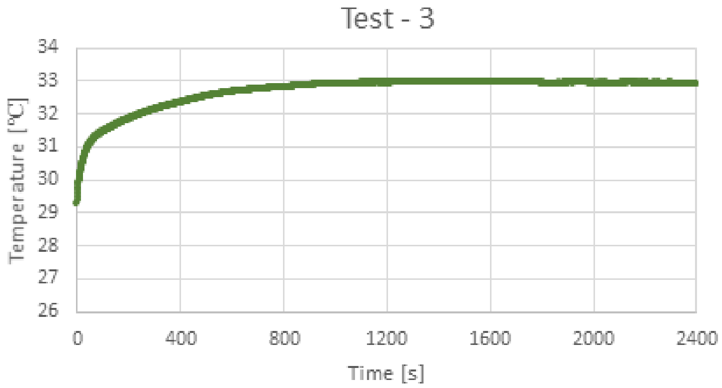

Fig 17 – Average Temperature obtained in wear used lubricant tests (Test-3)

recorded for the gear tooth flanks. Regarding the study of the hardness along the profile of the tooth, a decrease in hardness as the distance to the top of the tooth increased was observed, leading to conclude for the influence of carburization. On average, the hardness values tend to become constant after 5mm from the top of the tooth with the value of 470HV±1.92HV.

First pin-on-disc dry test (Test-1) was made to estimate a loss rate of material [mm^3], to both sample and pin (equations 1 and 2), with a 41.14N load applied, at a rotation speed of 350rpm, with a 50 minutes test period. Stops were made each 10 minutes to weight both sample and pin.

$$\Delta V_a = 0.0018 \times t + 0.0183 \quad (1)$$

$$\Delta V_p = 0.0015 \times t - 0.0024 \quad (2)$$

Second pin-on-disc dry test (Test-2) evaluated the volume loss in the material under different applied loads (16.93N, 30.84N, 34.35N and 41.14N), during 40 minutes at 350 rpm. In these tests the values of the friction coefficient registered were in the range 0.5 to 0.7 as expected. The registered values of friction force were 10N, 20N, 23N and 28N for test loads of 16.93N, 30.84M, 34.35N and 41.14N respectively. And the maximum temperatures registered in zone close to the contact area were 33ºC, 41ºC, 43ºC and 44,8ºC for the test loads of16.93N, 30.84M, 34.35N and 41.14N respectively. Equations 3 and 4 were obtained for the specimen and pin, relating the volume loss of material [mm^3] to the different applied loads.

$$\Delta V_a = 0.006 \times e^{0.1144 \times F_N} \quad (3)$$

$$\Delta V_p = 0.0031 \times e^{0.1036 \times F_N} \quad (4)$$

A third pin-on-disc test (Test-3) was performed with old lubricant, during 40 minutes at 350rpm, with an applied load of 82.75N. The volume losses were insignificants to both specimens and pin. It was concluded that the friction forces, friction coefficients and the temperature close to the tip of the pin decreased, in average, 8.7N, 0.1 and 33°C, respectively.

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