EFFECT OF THE CONTACT PRESSURE ON THE WEAR MODE TRANSITION IN MICRO-ABRASIVE WEAR TESTS OF WC-Co P20

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Abstract. *Recently, the micro-scale abrasive wear test has gained large acceptance in universities and research centers, due to its capacity to analyze the micro-abrasive wear behavior of a large number of materials. So far, the micro-scale abrasive studies available in literature refer to tests where the normal force (F_N) that pushes the ball against the specimen is kept constant during the test. Consequently, the contact pressure (P) acting on the system "specimen - abrasive particles - ball" decreases continuously, which may result in changes on the operating wear modes. In this work, tests were conducted with non-constant normal force, in order to maintain the contact pressure oscillating around a constant value. The objective was to analyze the effect of the contact pressure ("constant" and "non-constant") on the wear mode transition. The micro-abrasive wear tests were conducted with AISI 52100 steel balls, with diameter of 25,4 mm (1"), and specimens were made of tungsten carbide (WC-Co) class P20. The abrasive slurry was prepared with black silicon carbide (SiC) particles (average particle size of 5 μm) and distilled water. The results were analyzed in plots of A_g/A_p as a function of the test time (t), where A_p is the total projected area of the worn crater and A_g is the projected area fraction with grooving abrasion. The results allowed observing that the value of A_g/A_p was larger for the condition with constant contact pressure than non-constant contact pressure.*

Keywords*: micro-abrasive wear testing, contact pressure, wear modes, rolling abrasion, grooving abrasion*

1. INTRODUCTION

In micro-scale abrasion wear tests, a rotating ball is forced against the tested specimen, in the presence of an abrasive slurry, and the wear behavior is analyzed based on the dimensions of the crater formed during the test. This test has been applied in the study of the abrasive wear of metallic (Cozza, 2006; Cozza *et al.*, 2005; da Silva, 2003; da Silva *et al.*, 2005; Trezona *et al.*, 1999) and non-metallic (Baptista *et al.*, 2000; Batista *et al.*, 2001;2002a;b; Bello and Wood, 2005; Bose and Wood, 2005; Cozza *et al.*, 2006a;b;2007; Kattamis *et al.*, 1994; Mergler and Huis in 't Veld, 2003; Ramalho, 2005; Rutherford and Hutchings, 1996) materials and, depending on the equipment configuration, it is possible to apply normal loads (F_N) from 0.01 N (Adachi and Hutchings, 2003;2005) to 5 N (Bose and Wood, 2005; Cozza, 2006; Cozza *et al.*, 2005; Trezona *et al.*, 1999) and ball rotational speeds (*n*) up to 525 rpm (Cozza, 2006).

Two wear modes are observed during micro-scale abrasion wear tests: *rolling abrasion* results when the abrasive particles roll in the ball/specimen contact region, while *grooving abrasion* is observed when the abrasive particles slide in the contact region (Adachi and Hutchings, 2003;2005; Bose and Wood, 2005; Trezona *et al.*, 1999). Additionally, rolling abrasion and grooving abrasion can be generated simultaneously (Adachi and Hutchings, 2003;2005; Cozza, 2006; Cozza *et al.*, 2005;2006b;2007; Trezona *et al.*, 1999; Zeferino *et al.*, 2007). The type of wear mode has a significant effect on the wear rate of a tribologic system (Mergler and Huis in 't Veld, 2003; Trezona *et al.*, 1999).

For $h << D$, where *h* is the *crater depth* and *D* is the *diameter of the ball*, the *contact pressure* (*P*) may be calculated using Equations 1 or 2 (Cozza *et al.*, 2007):

$$P = \frac{F_N}{A_p} \tag{1}$$

$$P = \frac{F_N}{A_s} \tag{2}$$

where $A_p = \pi d^2/4$ is the *total projected area* and $A_s = \pi D h$ (Oberg *et al.*, 2000) is the *area of the spherical surface* of the worn crater; *d* is the *projected area diameter*.

For the condition $h << D$, the value of *d* is such that $A_p \approx A_s$ and the values of *P* calculated through Equations 1 and 2 are similar (Cozza *et al.*, 2007). In this work, the contact pressure was calculated using Equation 1.

The micro-scale abrasive studies available in literature refer to tests where the normal force that pushes the ball against the specimen is kept constant during the test (Adachi and Hutchings, 2003;2005; Batista *et al.*, 2001;2002a;b; Bello and Wood, 2003;2005; Bose and Wood, 2005; Ceschini *et al.*, 2006; Chen *et al.*, 2005; Cozza, 2006; Cozza *et al.*, 2005;2006a;b;2007; Gee *et al.*, 2003;2005; Gee and Wicks, 2000; Ramalho, 2005; Rutherford and Hutchings, 1996; Shipway and Hodge, 2000; Shipway and Hogg, 2005; Shipway and Howell, 2005; da Silva, 2003, da Silva *et al.*, 2005, Trezona *et al.*, 1999; Trezona and Hutchings, 1999). Consequently, the contact pressure acting on the system "*specimen - abrasive particles - ball*" decreases continuously, which may result in changes on the operating wear modes (Cozza *et al.*, 2007). In this work, tests were conducted with non-constant normal force, in order to maintain the contact pressure oscillating around a constant value. In the following paragraphs, tests with varying normal force will be referred as contact pressure, but, as indicated above, pressure was not precisely constant in these tests. The objective was to analyze the effect of the contact pressure ("constant" and "non-constant") on the wear mode transition.

2. EXPERIMENTAL PROCEDURE

2.1. Micro-scale abrasive wear equipment

An equipment with fixed-ball configuration (Figure 1), which was designed and assembled (Cozza, 2006; Cozza *et al.*, 2005;2006a;b;2007; Zeferino *et al.*, 2007) with differences from commercial fixed-ball equipment (Adachi and Hutchings, 2003; Batista *et al.*, 2001;2002a;b; Bello and Wood, 2003; Bose and Wood, 2005; Ceschini *et al.*, 2006; Chen *et al.*, 2005; Gee *et al.*, 2003;2005; Gee and Wicks, 2000; Shipway and Hodge, 2000; Shipway and Hogg, 2005; Shipway and Howell, 2005; Trezona *et al.*, 1999; Trezona and Hutchings, 1999) was used in the micro-scale abrasive wear tests. In this equipment, balls with a hole were used and the nut shown in Figure 1 was responsible for fixing the ball onto the shaft and transferring movement to the ball. This configuration eliminates the relative movement between the shaft and the ball and, theoretically, imposes mechanical restriction for ball movement in the direction parallel to the normal load (Cozza, 2006; Cozza *et al.*, 2006b;2007).

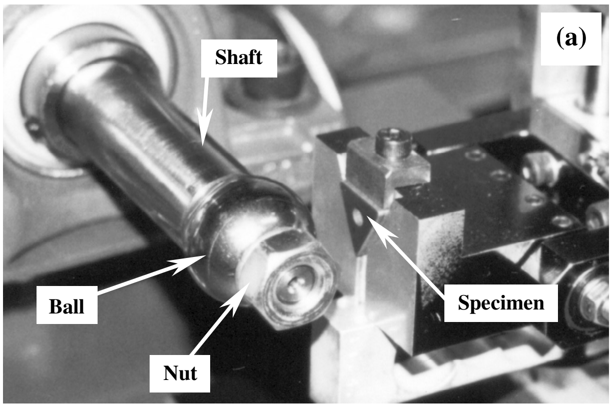

Figure 1. Detail of the ball and specimen assembly in the micro-scale abrasive equipment with fixed-ball configuration (Cozza, 2006; Cozza *et al.*, 2005;2006a;b;2007; Zeferino *et al.*, 2007).

2.2. Materials

The material analyzed in the tests was commercial ISO P20 tungsten carbide (WC-Co). The area available for the tests was triangular, with 16 mm edges. Balls made of AISI 52100 steel were used and presented a diameter of 25.4 mm (1"). Figure 2 presents the microstructures of the ISO P20 tungsten carbide (WC-Co) (Figure 2a) and AISI 52100 steel (Figure 2b) (Cozza, 2006; Cozza *et al.*, 2006a;2007; Zeferino *et al.*, 2007).

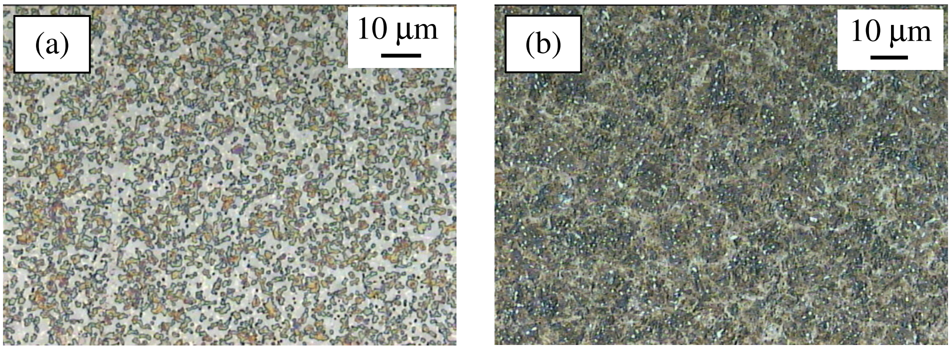

Figure 2. Microestruture: (a) ISO P20 tungsten carbide (WC-Co) and (b) AISI 52100 steel (Cozza, 2006; Cozza *et al.*, 2006a;2007; Zeferino *et al.*, 2007). Images obtained by optical microscope.

The abrasive used was black silicon carbide (SiC), from Alcoa, with average particle size of 5 μm (Izhevskyi, 2004). Figure 3 (Izhevskyi, 2004) presents a scanning electron micrograph of the abrasive used in this work (Figure 3a) and its particle size distribution (Figure 3b). The abrasive slurry was prepared as a mixture of 25% of SiC and 75% of distilled water, by volume. This mixture results in 1.045 g of SiC per cm^3 of distilled water (Cozza, 2006; Cozza *et al.*, 2005;2006a;b;2007).

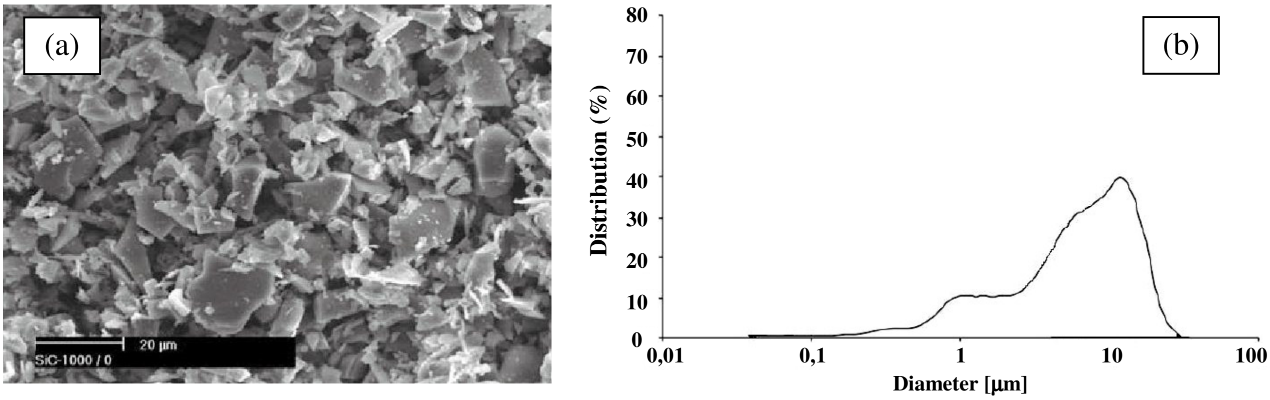

Figure 3. Characteristics of the SiC abrasive (Izhevskyi *et al.*, 2004). (a) Micrograph of the abrasive particles and (b) particle size distribution (Izhevskyi *et al.*, 2004).

Table 1 presents the hardness of the materials used in this work (specimens, balls and abrasive particles) (Cozza, 2006; Cozza *et al.*, 2005,2006a;2007; Zeferino *et al.*, 2007).

Table 1. Hardness of the materials (Cozza, 2006; Cozza *et al.*, 2005;2006a;2007; Zeferino *et al.*, 2007).

	Material	**Hardness - GPa [HV]**
Specimen	ISO P20 tungsten carbide (WC-Co)	11.7 [1193]
Ball	AISI 52100 steel	8.4 [856]
Abrasive particles	SiC	18.5 – 19 [1886 – 1937]

2.3. Wear tests

Table 2 shows the conditions selected for the experiments conducted with non-constant contact pressure (constant normal force) (Cozza, 2006; Cozza *et al.*, 2005;2006a;2007). The normal force was 1.25 N, and the ball rotational speed was n = 37.6 rpm, which was previously selected by Trezona *et al.* (1999). This value of n and the ball diameter (25.4 mm) result in a tangential sliding velocity at the external diameter of the ball of v = 0.05 m/s. Tests were run for six values of sliding distance (s), 8, 15, 20, 25, 35 and 40 meters, and four repetitions were conducted for each value of s.

Table 2. Conditions selected for the tests conducted with non-constant contact pressure (constant normal force) (Cozza, 2006; Cozza *et al.*, 2005;2006a;2007).

Condition selected	**1**	**2**	**3**	**4**	**5**	**6**
Normal force [N]	1.25	1.25	1.25	1.25	1.25	1.25
Ball rotational speed [rpm]	37.6	37.6	37.6	37.6	37.6	37.6
Sliding distance [m]	8	15	20	25	35	40
Test time	2 min 40 s	5 min	6 min 40 s	8 min 20 s	11 min 40 s	13 min 20 s
Abrasive slurry supply	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s
Number of repetitions	4	4	4	4	4	4

Table 3 presents the conditions selected for the tests conducted with constant contact pressure (Zeferino *et al.*, 2007). The contact pressure (0.73 MPa) is an average value obtained with the values of the contact pressures calculated during each of the steps at different sliding distances. The ball rotational speed and sliding distances remained the same as those defined for non-constant contact pressure tests.

The abrasive slurry was continuously agitated and manually fed to the ball/specimen contact, with the help of a dropper.

Table 3. Conditions selected for the tests conducted with constant contact pressure (Zeferino *et al.*, 2007).

Condition selected	**1**	**2**	**3**	**4**	**5**	**6**
Contact pressure [MPa]	0.73	0.73	0.73	0.73	0.73	0.73
Ball rotational speed [rpm]	37.6	37.6	37.6	37.6	37.6	37.6
Sliding distance [m]	8	15	20	25	35	40
Test time	2 min 40 s	5 min	6 min 40 s	8 min 20 s	11 min 40 s	13 min 20 s
Abrasive slurry supply	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s	1 drop / 10 s
Number of repetitions	3	3	3	3	3	3

3. RESULTS AND DISCUSSION

3.1. Constant contact pressure

For the condition of constant contact pressure, Figure 4 presents an average of the experimental contact pressures obtained for each of the three repetitions at different values of s (Zeferino *et al.*, 2007). At the end of each test, the total projected area of the worn crater was measured. Then, the normal force was readjusted to obtain a contact pressure 3% higher or lower than 0.73 MPa. The value 3% was obtained experimentally (Zeferino *et al.*, 2007).

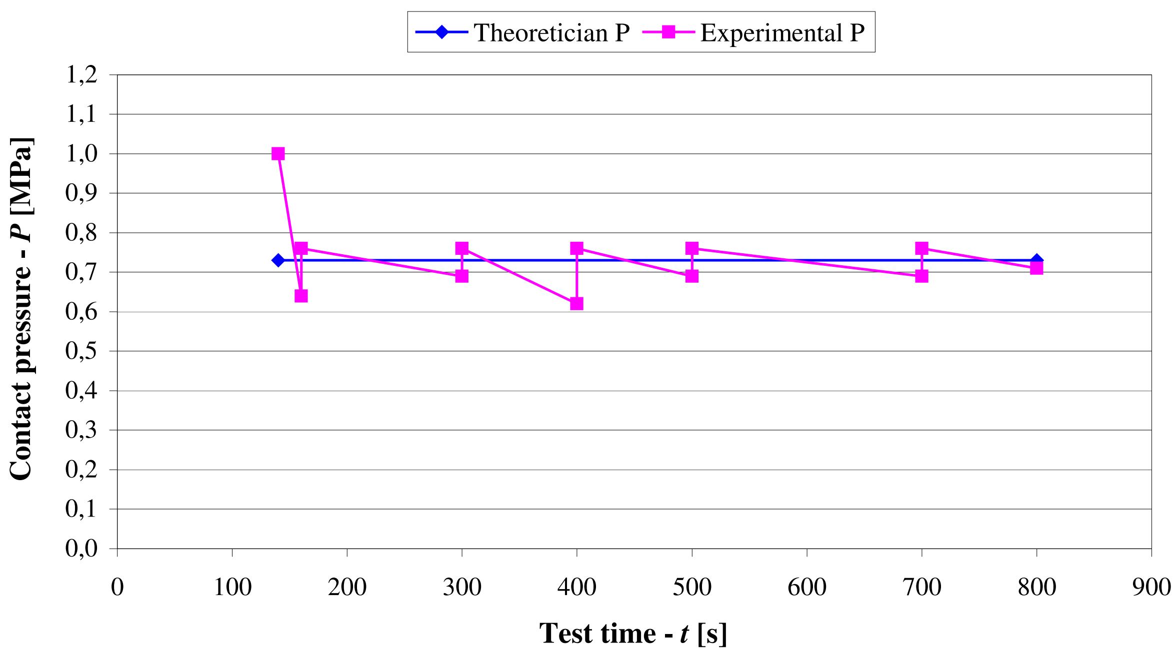

Figure 4. Experimental and theoretician contact pressure (Zeferino *et al.*, 2007).

3.2. Influence of the contact pressure on the grooving and rolling abrasion wear modes

Figure 5 presents the definition of the *total projected area* (A_p) and *projected area fraction with grooving abrasion* (A_g) (Cozza *et al.*, 2007). In this work, A_p and A_g were calculated following this procedure with the help of a CAD software.

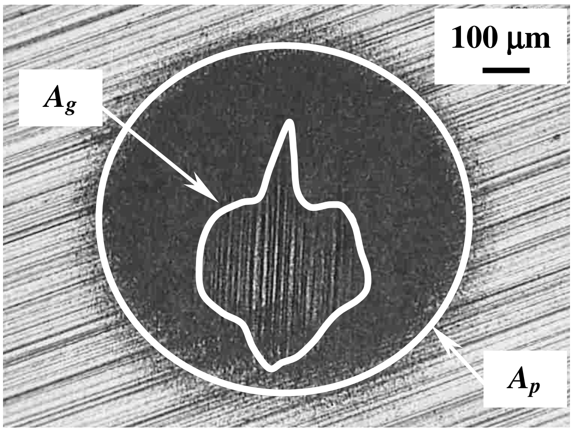

Figure 5. ISO P20 tungsten carbide (WC-Co). Definition of A_p and A_g (Cozza *et al.*, 2007).

Figure 6 presents a plot of A_p, A_g and A_r as a function of the *test time* (t). A_r is the *projected area fraction with rolling abrasion*, and this quantify was calculated using Equation 3:

$$A_r = A_p - A_g \tag{3}$$

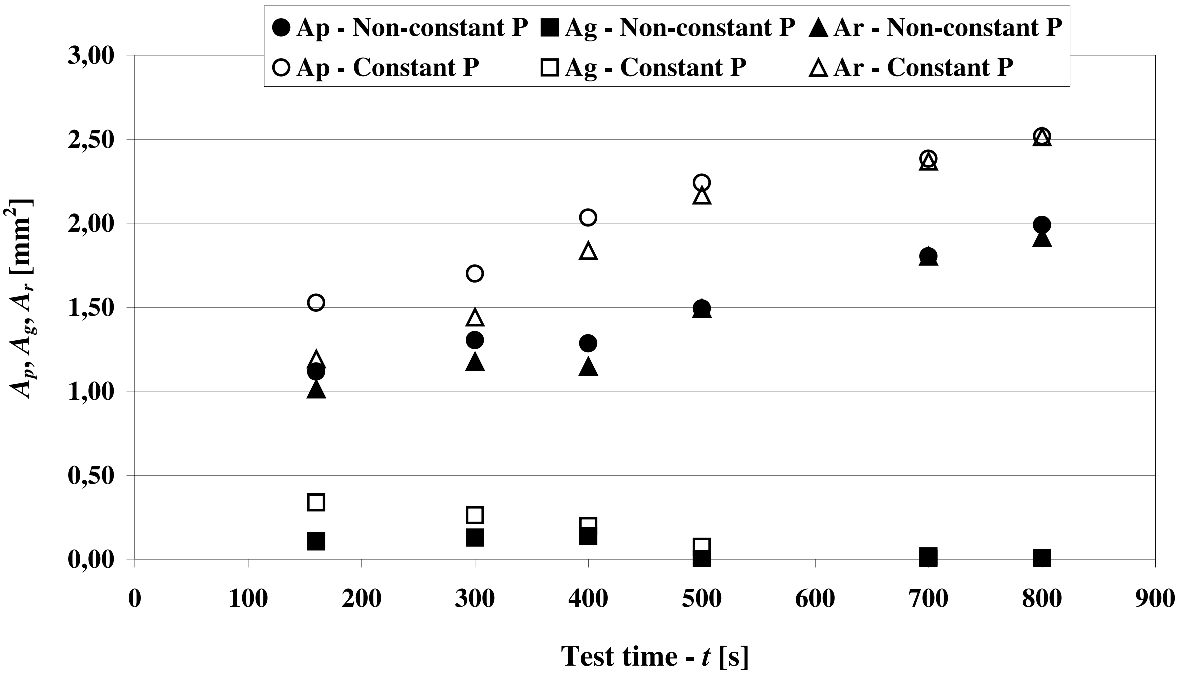

Figure 6. A_p, A_g and A_r as a function of the test time.

For the conditions of constant contact pressure, the values of A_p, A_g and A_r were larger than the conditions of non-constant contact pressure, which was expected since the force was gradually increased throughout the constant contact pressure tests.

During the tests with constant normal force (non-constant contact pressure), the total projected area of each crater increased gradually. Consequently, a larger quantity of abrasive particles penetrated the specimen/ball contact. With the increase of the quantity of abrasive particles between the region specimen/ball, the normal force acting on each abrasive particle is lower. Then, it can favor the occurrence of rolling abrasion (Cozza *et al.*, 2007). On other hand, in the condition with constant contact pressure, test evolution also result in an increase of abrasive particles between the specimen and the ball, but, in this case, there is an increase in the normal force necessary to keep the contact pressure constant. Then, in this case, there should not be a decrease on the normal force acting on each abrasive particle.

Figure 7 presents the ratio A_g/A_p as a function of the test time. A general trend was observed in the two cases (constant and non-constant contact pressure). Initial test conditions always resulted in craters presenting evidences of both grooving and rolling abrasion.

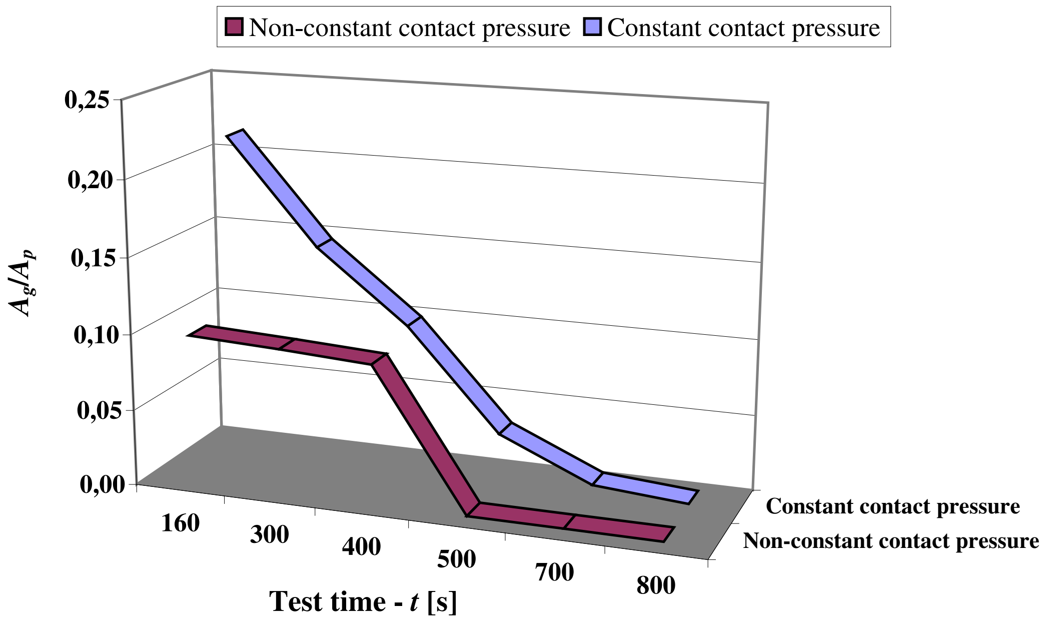

Figure 7. A_g/A_p as a function of the test time.

For the condition of non-constant contact pressure, the wear mode transition occurred earlier than for the condition of constant contact pressure, approximately at 500 s. However, the condition with constant pressure was unable to maintain a constant A_g/A_p ratio throughout the tests as initially predicted. Further research is still necessary to understand the results.

3.3. Constant regime of wear

Figure 8 presents the evolution of the *wear volume* (*V*) as a function of the test time, for the conditions of constant and non-constant contact pressure.

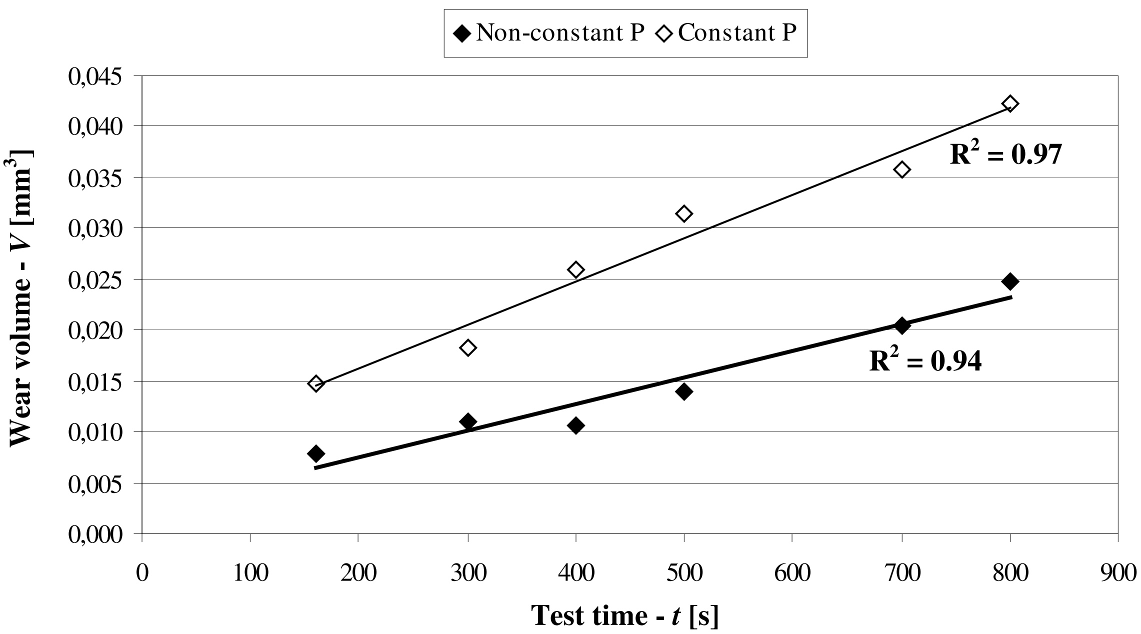

Figure 8. Wear volume as a function of the test time.

For the condition with non-constant contact pressure, the constant regime of wear is obtained when the wear volume presents a linear dependence with the test time or sliding distance (Bose and Wood, 2005; Gee *et al.*, 2005; Ramalho, 2005; Trezona *et al.*, 1999).

Then, in this work, the constant regime of wear was obtained for the tests conducted with non-constant contact pressure. The experiments conducted on constant contact pressure indicate that this condition did not seem to affect the linear dependence of wear volume with the test time.

4. CONCLUSIONS

The results obtained in this work indicated that:

1) The conditions of constant or non-constant contact pressure had an important effect on the occurrence of the abrasive wear modes and their transitions. In the condition of non-constant contact pressure, the transition from grooving abrasion to pure rolling abrasion occurred earlier than for constant contact pressure.
2) In the condition of constant contact pressure, the wear volume presented a linear dependence with the test time, and this can be a indicative that the constant regime of wear was obtained.

5. ACKNOWLEDGEMENTS

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