WEAR RESISTANCE OF GREY CAST IRON

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Abstract: *Present work investigates the wear resistance of two grey cast iron batches, using the pin-on-disc test, according to the ASTM G99-95 Standard, which pins were plasma nitrided high speed steel with 1300 HV. The specimens, in disc shape, diameter of 62 mm, thickness of 4mm, machined from grey cast iron, constituted by two different chemical composition, codified as batch type A and type B respectively, were tested on the two disc faces, but one face each time, in a total of 5 specimens. The mean disc hardness varied between 206 to 220 HV. Normal loads of 20 N, 30 N and 40 N were applied, total sliding distance of 2400 m were performed with sliding velocity of 0,6 m/s, the environmental temperature were 25^{o}C and the humidity were controlled at 45%. In general, from the analysis of the cumulative lost volume versus sliding distance curves presented in the graphs, it is observed greater wear in the disc type A than type B gray cast iron. It is noted that the wear rate tends to zero at the final part of the sliding distance. This can be due to the wear track enlargement and, consequently, the real pin contact pressure against the disc decreases, producing a lower wear rate. The curves presents three phases or distinct regimes: regime 1 of initial run in stage, regime 2 of constant wear rate and phase 3 of wear rate tending to zero. Different wear rate in face a or b in the same disc was observed and is due to different hardness and, possibly, due to the machining process in the faces.*

Key-words : *Wear test, grey cast iron, pin-on-disc, wear resistance.*

1. Introduction

Cast irons are broadly used in the fabrication of pieces mainly by the automotive industry and the metal-mechanics sector due to its low cost among the metals, good machinability and castability to produce pieces of complex shape. Cast irons are classified according to its chemical composition and the various graphite shapes and percentage in the microstructure: white, gray, ductile or nodular, malleable and vermicular. In gray cast iron, graphite is distributed in the matrix microstructure as large flakes (lamella) and as fine flakes inside the pearlite phase (present 50% in volume) (Kalpakjian, 1985). The graphite in the matrix microstructure play the role as solid lubricant, i.e., gray cast iron has an intrinsic characteristic of a self solid lubricant material in the sliding contact and in machining processes. However, the effect of graphite percentage and shape on the wear resistance and fatigue has not been studied extensively yet. Gray cast iron is a common material for application such as in brake discs and cylinder liners in cars (Anderson, 1992).

In many applications as gears, shafts, journal bearings, pistons, engine blocks and other components submitted to wear, it is desirable to have high surface hardness combined with a good material toughness in the bulk. Cast iron hardness results from the microstructure type and presence of hard carbides in the matrix. The different microstructure types possible in cast iron are: ferrite, pearlite, martensite and bainite. Thus, through heat treatment or thermo-chemical treatment applied to cast irons, it is feasible to obtain a good combination of *mechanical strength* and *wear resistance.* In addition, due to the load type that generally occurs in mechanical components, it is also necessary that the material have properties such as high hardness and high fracture toughness, as many components are subjected to impact loads and the material can present surface or bulk microcracks originated from casting, machining or heat treatment processes, leading to fracture. These microcracks can be considered stable if the mechanical property fracture toughness is sufficiently high.

Mechanical strength is normally defined as the material yield stress or the ultimate tensile stress. On the other hand, *wear* is defined as *"progressive loss of mass from a solid surface in relative movement, leading to damage or fracture"*. Wear can be *mild* or *severe*, depending on the contact conditions between the surfaces, pressure and temperature contact and the material hardness. The contact conditions or contact severity is defined by an equation that relates these variables as seen below.

Austempered spheroidal graphite cast iron has good properties as wear resistance, toughness, tensile strength and fatigue resistance (Hatate et al., 2001). In the study conducted by Hatate et al. on the influences of graphite shape on wear resistance, they concluded that decreasing the graphite nodularity from spheroidal shape to vermicular and flake leads to a significant decrease in the wear resistance.

Material wear resistance is usually obtained by carrying out wear tests in laboratory equipment named tribometer. A standard laboratory test that simulates the severe conditions of wear in mechanical components under certain situations is the pin-on-disc test, according to the ASTM G99-95 standard (ASTM, 1995). In this apparatus, the test is performed with a selected constant total sliding distance, a constant normal load on the pin, a constant sliding velocity (Bressan at al., 2001a) and controlled conditions of temperature and humidity.

The aim of the present work was to investigate the wear resistance of two batches of gray cast iron specimens, using the pin-on-disc test, according to the ASTM G99-95 standard and to a new methodology of measuring the track width as function of the sliding distance. The counterface were discs of gray cast iron and the pins were plasma nitrided high speed steel of 1300 HV.

2. Laboratory Wear Testing

Scientific and technological researches about wear resistance are a relevant issue in the selection of material and design of mechanical components as mentioned above. In consequence, a great number of laboratory tests were developed aimed at measuring wear resistance under controlled conditions similar to the service conditions and to rank the materials for tribological applications. The American Society for Testing Materials – ASTM, describes more than 30 experimental methods to measure wear (Williams, 1997).

The correlation between the laboratory simulation tests and its application in the design of a component is of great importance to the practical tribology. However, the various variables that influences wear make this correlation rather difficult. Wear resistance and friction coefficient are not material characteristic properties, but depend upon the material properties, surface topography and the process parameters as load, sliding velocity and environment: temperature and humidity.

The experimental wear results performed in laboratory are analyzed through the Archad´s equation (Hutchings, 1995) or Rabinowicz´s equation (Rabinowicz at al., 1961) which evaluates the wear rate and the wear coefficient, relating the cumulative lost volume per unit sliding distance with the wear resistance by the equation,

$$Q = \frac{V}{S} = K\frac{F_N}{H} \qquad (mm^3/m) \tag{1}$$

where Q is the parameter that measure the *wear ratio* or *"wear rate"* (cumulative lost volume V or lost mass per unit sliding distance S), F_N is the applied normal load, H is the softer material hardness and K is the *wear coefficient*: is non-dimensional and less than 1. In general, *wear resistance* is defined as *1/K* . Therefore, the wear coefficient is given by,

$$K = \frac{Q.H}{F_N} = K_S.H \tag{2}$$

where K_S is the *specific wear coefficient* ($K_S = Q/F_N$) which unit is $mm^3/m.N$. Note that both coefficient are for the softer material. In the pin-on-disc test, the softer material is the disc. The disc or pin lost volume is obtained from,

$$V = m/\rho \qquad (m = \text{mass} ;\ \rho = \text{density}) \tag{3}$$

The wear coefficient K is of fundamental importance and provides a valuable way for comparing the rigor of the wear process in different tribological systems. Therefore, the Archard wear equation provides the relevant parameters that describes the wear rate through the coefficient K, however, its validity cannot be used to confirm the occurrence or not of a certain material removal mechanism. It is necessary to employ the optical or electronic microscope to identify the main acting wear mechanism.

Archad developed this equation for sliding wear, but latter has been shown that it can be applied to wear between two abrasive bodies, involving plastic flow, where angular hard particles are pushed against a contact surface.

The parameter K can be used to compare the wear severity of the same material under different conditions, and to compare the wear resistance of different materials under similar conditions. The material and the tribological system choice influence the wear coefficient value. The pin-on-disc test has been used also to evaluate the wear resistance of the harder material, the pin (Bressan at al., 2001b). In the wear by three body abrasion, the wear mechanism is micro-abrasion and depend on two parameters: the contact severity, S´, and the hardness ratio between the disc and particle, H_d / H_p . The *contact severity S´* is given by (Bose at al., 2005),

$$S' = F_N / A\upsilon H' \tag{4}$$

where A= contact area, υ = particle volumetric fraction and $H' = 1/H_d + 1/H_p$. Two kinds of abrasion wear by hard particle have been identified: *"wear by two bodies"* and *"wear by three bodies"* (Zum Gahr, 1998). Wear is *"by two bodies"* when involve two solids in contact and relative motion only, named *sliding wear*. On the other hand, in the *"wear by three bodies"* there are hard particles between the surfaces in relative motion that produces abrasive wear. In addition, abrasive wear can be due to the particle sliding mechanism or indentation in the surface. Hard particle sliding produce the abrasion wear mechanisms as micro-grooving or ploughing, wedge formation and micro-cutting (micro-ship formation).

In relation to the nature of wear phenomena, the mechanism can be *plastic deformation* (mechanic phenomena) of superficial asperities (producing micro-grooving and micro-cutting), *micro-cracking* (mechanic phenomena) and *adhesion* (chemical phenomena) of material on the surface, transferring material from one to another body.

3. Materials and Experimental Procedure

The specimens were produced in discs shapes from gray cast iron, constituted by two different chemical compositions, named batch type A and type B respectively, in a total of 5 discs in batch A and 3 discs in batch B. The chemical compositions are presented in Table 1 and 2. The difference is very low and is due to more content of mainly chromium and little more nickel and tin elements in batch A.

Table 1 – Chemical composition in % weight element of gray cast iron discs in batch A.

Element	%C	%Si	%Mn	%Cr	%Mo	%Cu	%Ni	%P	%S	%Sn
Minimum	3,50	2,10	0,40	0,0	0,0	0,40	0,0	0,40	0,05	0,05
Maximum	3,80	2,40	0,50	0,120	0,06	0,50	0,06	0,50	0,090	0,100
Found	3,57	2,17	0,45	0,25	0,017	0,458	0,042	0,445	0,076	0,064

Table 2 – Chemical composition in % weight element of gray cast iron discs in batch B.

Element	%C	%Si	%Mn	%Cr	%Mo	%Cu	%Ni	%P	%S	%Sn
Minimum	3,50	2,10	0,40	0,0	0,0	0,40	0,0	0,40	0,05	0,05
Maximum	3,80	2,40	0,50	0,120	0,06	0,50	0,06	0,50	0,090	0,100
Found	3,54	2,14	0,45	0,125	0	0,45	0,03	0,44	0,071	0,025

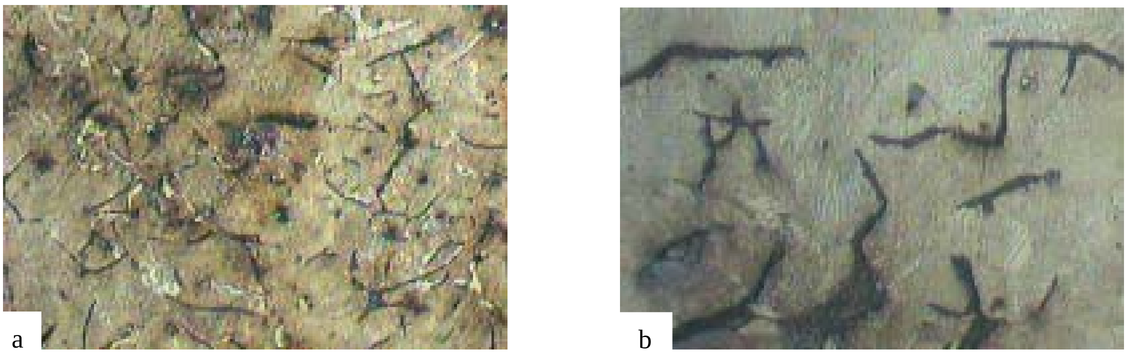

Figure 1. Micrographs of gray cast iron in batch A. Presence of graphite flakes and carbides in a) surface - 200x. b) interior - 500x. Presence of pearlite phase and coarse graphite lamella.

In Figure 1, the microstructure of present work gray cast iron from batch A is observed. The micrographs from batch B is similar. In micrograph (b) the presence of pearlite phase and coarse graphite lamella is noted.

The wear resistance results were obtained from carrying out the wear tests in a pin-on-disc apparatus. Each experimental test uses a set of selected constant operation conditions: constant total sliding distance, constant normal load on the pin and sliding velocity (Bressan at al., 2001a). Table 3 shows the used parameters during the tests in the present investigations. For each load condition, two test were performed in the same disc, i.e., same normal load on both disc faces against nitrided high speed steel.

Table 3- Pin-on-disc wear testing parameters used.

Velocity (m/s)	Load 20N (Kgf)	Load 30N (Kgf)	Load 40N (Kgf)	Sliding distance (m)	Track radius (mm)
0,6	1,930	2,953	4,000	2400	14,3

Figure 2. Gray cast iron disc or counterface and steel pin for testing in the pin-on-disc apparatus.

3.1 Test Specimens

Pin. The pin test specimens were made from a VWM2 tool steel bar. The fabrication of the pins were performed by conventional methods as machining and milling to obtain the appropriate geometry with a spherical tip which radius was approximately 10 mm, see Figure 2. After machining, the pins were heat treated and plasma nitrided to increase its hardness to 1300 HV, according to tooling requirements.

Disc. The counterface or disks, see Figure 2, were obtained by sawing out a gray cast iron bar into pieces which have 5 mm in thickness by diameter 62 mm. The disk was machined to the appropriate dimensions and roughness for testing. The measured hardness on the disc faces varied from 206 HV to 220 HV. Figure 1 shows the microstructure of the disk surface. Pearlite phase, coarse graphite lamella distribution and size, and carbide are observed.

3.2 Procedure for Pin-on-disk Testing

Initially, the specimens followed a rigorous preparation procedure in order to eliminate any trace of dust, debris or oxidation, using a flux of compressed air and a clean cloth. After, pin and disk were weighted in an analytical balance, with 0.1 mg of accuracy, for determining its initial mass before the tests. Then, pin was fixed in exactly the same position as initially marked.

The pin-on-disk apparatus parameters as the track radius, disk rotation and the revolutions counter were adjusted to the selected conditions: see Table 3. The pin-on-disk apparatus was equipped with a large glass campanula that covered the specimens. Temperature and humidity inside the campanula were kept at approximately 25^{o}C and 42 to 45% of relative humidity. Three types of normal loads on pin were selected for each test: 20 N, 30 N and 40 N. The counter was set to stop the test at every 200 m of pin sliding distance in order to allow measuring the intermediate mass lost for pin and disk. Each test was considered completed for 2400 m sliding distance. A full specimens cleaning, using a flux of compressed air and a cloth with ethylic alcohol 99,5% always preceded these measurements. Before weighting, the specimens were dried out in a furnace at 80^{o}C for 10 min to avoid any solvent in the specimen and to evaluate the real mass lost from the pin, ball and disk.

4. Results and discussions

The disc lost or worn mass was converted to lost volume by the division of density, according to equation 3. The results seen in figure 3 refers to the lost volume values for five discs from batch A against the nitrided high speed steel pins, covering the total sliding distance of 2400 m and pin normal loads of 20 N , 30 N and 40 N on both disc faces. For the same disc and load, the wear rate is different, possibly due to the difference in hardness, size of carbides and graphite distribution and size in each disc face. In general, the curve tendency is to decrease the wear rate with the sliding distance, tending to zero in final part of the space interval. That is, the instantaneous wear rate (tangent to the curve) diminish with the sliding distance. This is due probably to the widening of the worn track w in the disc, as seen in figure 4, decreasing the real contact pressure and, consequently, decreasing the wear rate. Furthermore, it can be due to the graphite action as solid lubricant in the surface contact between pin and disc.

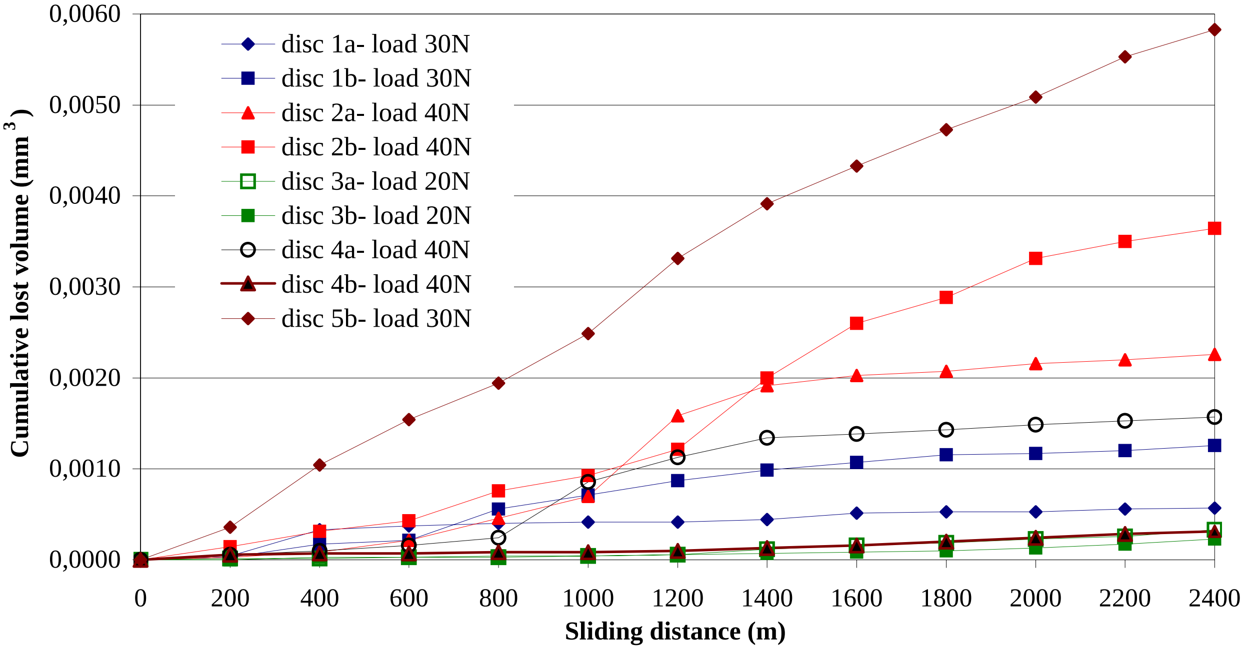

Figure 3. Evolution of cumulative lost volume of gray cast iron discs from batch A in function of the sliding distance in the pin-on-disc test.

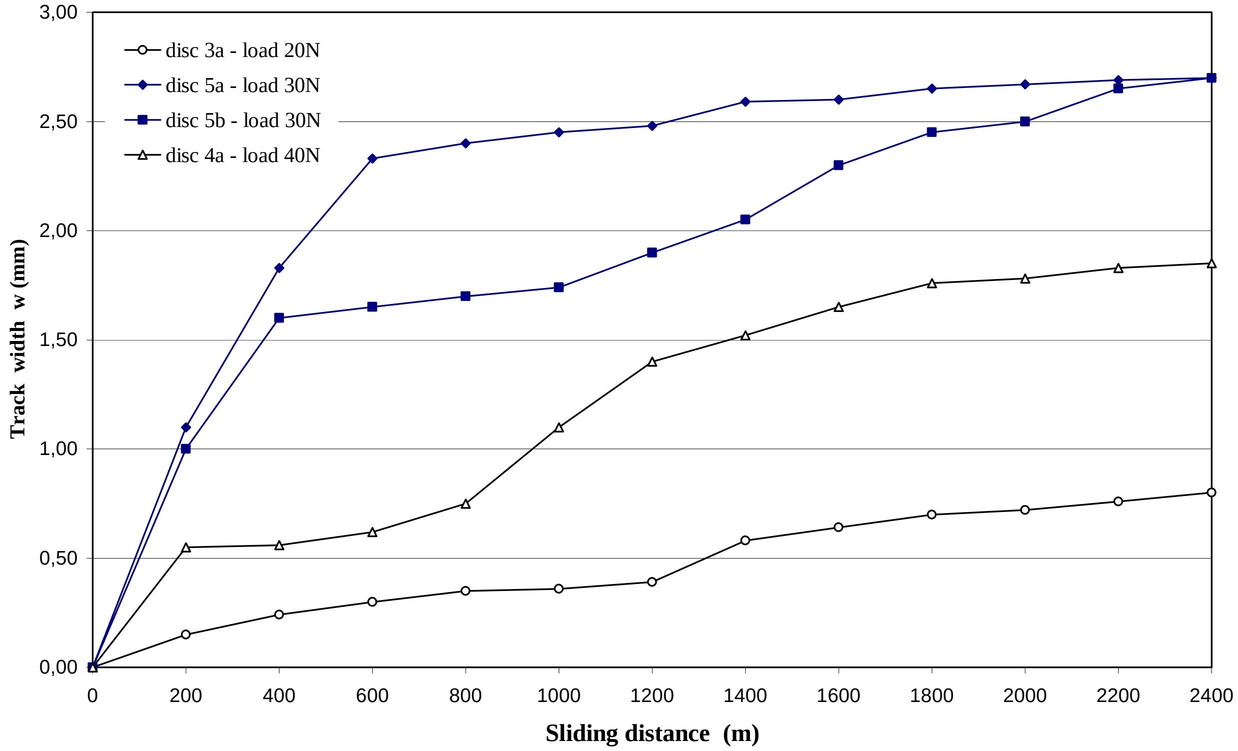

Figura 4. Evolution of track width w on the gray cast iron discs from batch A as function of the sliding distance.

In general, the experimental lost volume curves are not linear and, thus, do not follow precisely the Archad Law of linear increase with distance and load. There are curves with superior wear ratio for lower loads for batch A and B. This can be due to more effective action of solid lubricant by graphite at higher loads, reducing friction and mass losses.

In figure 4, the evolution of the disc worn track width w with the sliding distance is presented. It is observed that there are three distinct wear regimes: initial stage of run in with high wear rate (up to about 400 m), intermediate stage or secondary stage of lower but constant wear rate, and the third stage of wear rate tending to zero. The greater load of 40 N did not yield the greater wear rate as observed in this figure. This is due to the fact that the real contact pressure between pin and disc decreased with the sliding distance as the load is constant and the contact area increases. The different wear ratio of face a or b, is due to the variation in hardness: varied from 206 to 219 HV.

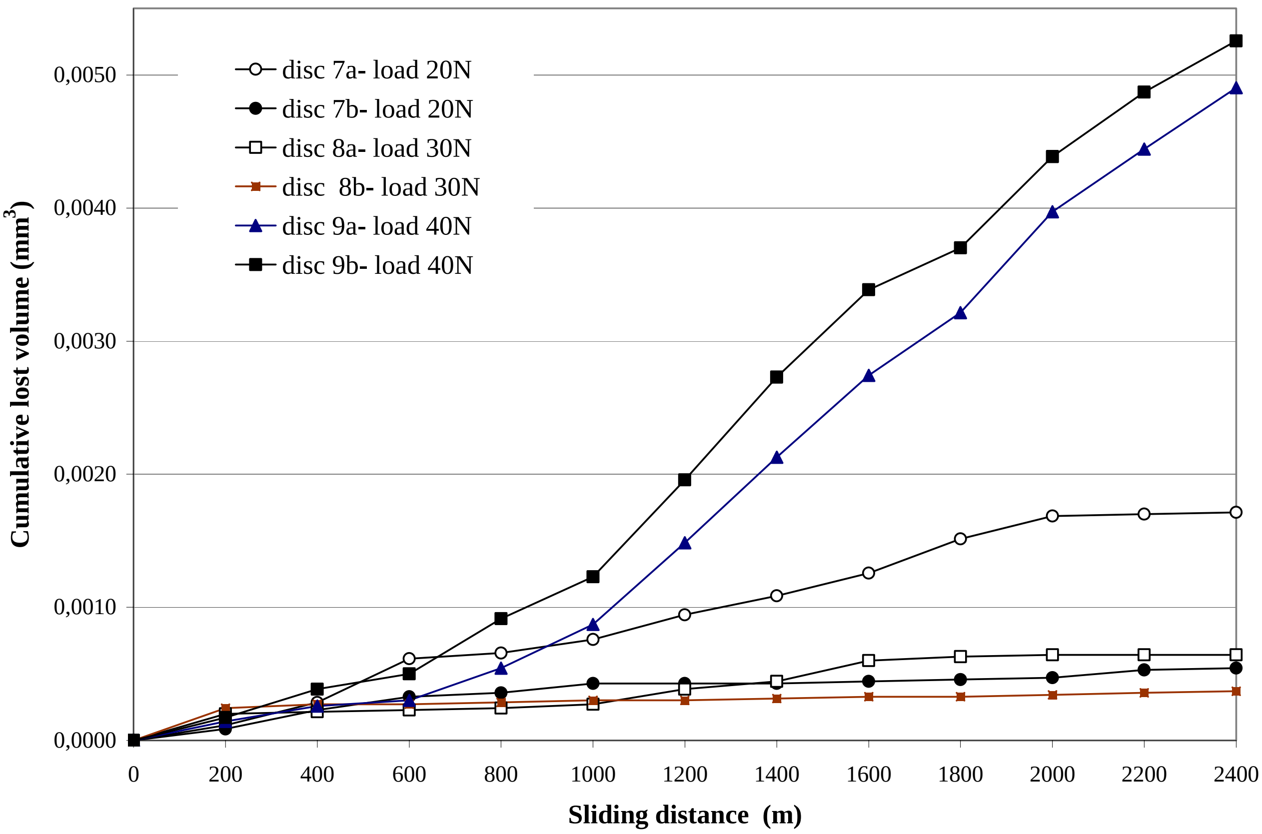

Figure 5. Evolution of cumulative lost volume of gray cast iron discs from batch B in function of the sliding distance in the pin-on-disc test.

In figure 5, the cumulative lost volume for discs from batch B with lower element contents is presented. The curves are different, but have the same tendency and show the three wear regimes. For load 40 N the wear ratio in the second stage is greater than the initial stage, possibly due to the abrasion action of the hard carbide particle extracted from the matrix. However, the second stage wear ratio is proportional to the load as predicted by the Archad equation. Comparing the wear ratio of batch A and B, it is concluded that batch B has greater wear resistance, although has lower element content. This is possibly due to the carbide content and size in the matrix.

5. Conclusions

From the pin-on-disc experimental results of wear tests for lost volume versus sliding distance of gray cast iron discs against nitrided high speed steel pins and from the micrograph observations, it can be concluded the following statements:

- In general, the tendency of the lost volume curve with the sliding distance is to decrease the wear ratio at the curve final space interval. That is, the instantaneous wear ratio (tangent to the curve) diminishes with the sliding distance and tends to zero at the end of the curve. The disc wear track width curve presents three distinct regimes: initial stage of run in with high wear rate (up to about 400 m), intermediate stage or secondary stage of lower but constant wear rate, and the third stage of wear rate tending to zero. This is due probably to the widening of the worn track width w in the disc and the action of graphite as solid lubricant.
- The experimental wear curves for gray cast iron from batch B obeys the Archad Law of linear increase in the wear rate with the load, but the wear rate is not constant with distance.
- However, the experimental wear curves for gray cast iron from batch A does not follows the Archad Law as there are curves with superior wear rate for lower loads. This can be due to more effective action by graphite as solid lubricant at higher loads, reducing friction and mass losses. Also it can be due to material heterogeneities as carbide size.
- Comparing the wear rate of batch A and B, it is concluded that gray cast iron from batch B with lower element content has superior wear resistance than batch A for same applied load.
- In the same disc, the wear rate are slightly different for face a and b. This is possibly to the hardness difference which varied between 206 to 219 HV and/or the machining operation.

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