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INFLUENCE OF LOAD ON WEAR RATE AND FRICTION OF AISI 1005 STEEL SHEET EVALUATED BY BALL-ON-DISC TESTING

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Abstract: *Present work investigates in detail the relationship between wear rate, friction coefficient and applied normal load of steel discs and balls in ball-on-disc testing. The wear testing by sliding was carried out in a ball-on-disc tribometer whose counter face or discs were AISI 1005 steel of thickness 2.88 mm and exhibiting average Vickers micro-hardness of 120 HV0.5. The balls were spheres of AISI 52100 steel plasma either plasma nitrided or plasma nitrided plus MOCVD coated with* Al_2O_3*; all spheres had diameter of approximately 10 mm. The discs and balls wear behavior were evaluated, using sliding velocity of 0.45 m/s, total sliding distance of 2700 m, normal loads of 1.96 N, 5.1 N, 7.1 N, 10 N, 15.1 N, 19 N and 29 N, and a controlled room temperature of 26 °C and humidity between 40 % to 50 %. The friction coefficients were measured on-line during testing. From the analysis of the plotted curves of friction coefficient and disc cumulative lost volume versus sliding distance the various wear rates were calculated and the relationship between the normal load, friction coefficient and wear rate were experimentally examined. The nominal pressure obtained by dividing the normal load per measured worn contact area in the ball decreased with sliding distance. From the analysis of the sphere cumulative lost volume versus the worn area, the relationship between the ball worn area and its lost volume were also experimentally examined and the curve was approximately linear. The wear mechanisms were also investigated by the friction coefficient values and by the scanning electron microscope: micro-delamination, adhesion and the formation of intermediary layer. Due to the different normal loads, ball hardness and variations of toughness, different wear rates, wear coefficients and friction coefficients were observed and discussed.*

Keywords *: Ball-on-disc***,** *AISI 1005 steel, wear behavior, AISI 52100, alumina.*

1. INTRODUCTION

Wear resistance and friction coefficients are relevant issues in the material selection in mechanical components and tooling design, thus, consequently, theoretical models and experimental laboratory wear tests have been developed aimed at predicting and measuring friction and wear resistance of materials under controlled conditions similar to working operations.

When two contacting surfaces slide against each other, one or both surfaces must wear. A simple theoretical model of sliding wear was presented by Holm and Archard (Archard, 1953). Although originally developed for metals, the wear model has been applied with success to several materials, including composites. Archard´s analysis takes into account the surface topography or roughness: the surface contact area occurs only in few asperities tips, thus, the real contact area is a fraction of the nominal area.

Regarding the nature of friction phenomena, nowadays it is recognized that the real contact area occurs in the surface asperity tips, thus, the real contact area is much less than the nominal area. Consequently, friction is due to the mechanisms of elastic and plastic deformations and adhesion of roughness tips of surfaces in relative motion, i.e., elastic strain, plastic strain and adhesion,

$$\mu = \mu_{elastic} + \mu_{plastic} + \mu_{adhesion} \qquad (1)$$

During the initial stage of surfaces sliding or "running in" the planning of the asperity tips occurs modifying the friction coefficient. In metals, if the contact pressure between the roughness tips is high enough, the oxide film can break and a direct contact metal to metal can be established and the onset of adhesion can occur, increasing the friction coefficient. In addition, in sliding wear there is always the formation of an intermediary layer or third body or diffusion layer or tribomaterial which is produced on solid surfaces under dry sliding contact (Hutchings, 1985; Rigney, 2007) and that affect the wear. It is also named transfer layer, fragmented layer, Beilby layer, adherence layer, highly deformed layer or nano-crystalline layer. Molecular dynamic simulations (Rigney, 2007) have shown the evolution of this layer with sliding time. Various examples on the evolution of the intermediary layer for two distinct solid materials A and B in sliding contact were presented. The vorticity effect and the interface instability in the mechanical mixing of materials A and B were shown. The mixing phenomena in the intermediary layer is similar to fluid flow. Thus, the molecular dynamic simulation allowed them to predict the transfer layer of nano-crystals, the increase in free volume, the instability of the sliding interface and vorticity of mechanical mixing in the interface.

In general, the wear mechanisms can be classified as plastic deformation of roughness, producing plowing and micro-cutting, micro-delamination or formation of micro-flakes, surface fatigue, micro-cracking, and material adhesion, transferring material from one solid to another.

In 1953, Archad (1953) presented an empirical linear equation relating the cumulative lost volume per sliding unit or the wear rate of metals to the area of plastic contact in sliding wear,

$$Q = K \, . \, A \qquad (2)$$

Q is the wear rate (lost volume per unit of time or per unit of sliding distance), K is the wear coefficient (non-dimensional), A is the plastic contact area. This is a linear equation of lost volume to the contact area of wear and K is the constant of proportionality. This equation was later reformulated to introduce an equation for the plastic contact area between the solid surfaces under wear in relative motion derived from the hardness definition $H = F_N/A$,

$$A = F_N / H \qquad (3)$$

F_N is the normal applied force and H is the material Vickers hardness. However, this equation does not take into consideration the contact pressure intensity which can vary from zero to high pressure values in real contact problems. Thus, eq. (2) was rearranged to the following well known Archad´s equation for sliding and abrasive wear,

$$Q = \frac{V}{S} = K \frac{F_N}{H} \qquad (4)$$

The goal of the present paper is to investigate experimentally the relationship amongst wear rate, friction coefficient, wear area, nominal contact pressure and applied normal load of steel discs and balls in ball-on-disc testing.

2. LABORATORY WEAR AND FRICTION TESTING

Laboratory wear and friction tests were developed aimed at measuring friction and wear resistance under controlled conditions similar to working situations. Wear testing can be used to investigate friction coefficient, wear resistance and wear mechanisms in order to enhance and classify the materials for these applications. The correlation among the laboratory simulation tests and its application in design of mechanical components and tooling is of great importance for practical tribology. However, the diversity of variables that influence wear makes this correlation sometimes rather difficult. Wear resistance and friction coefficient are not characteristic material properties, but depend on both the material properties and surface geometric features as well as on the wear process parameters such as load, temperature, sliding velocity and environment. The experimental results of wear carried out in the laboratory are commonly analyzed by the Archad´s (Hutchings, 1995) or Rabinowicz´s equation (1965) that assess the wear rate and the wear coefficient, relating the cumulative lost volume per sliding unit with the wear resistance through the linear equation (Hutchings, 1995). In general, the *wear resistance* is defined as 1/K or 1/Q. Therefore, the *wear coefficient* is given by,

$$K = \frac{Q.H}{F_N} = K_S \, .H \qquad (5)$$

where K_S is the specific wear coefficient ($K_S = Q/F_N$) whose unit is $mm^3/m.N$. where Q is the parameter that measures the wear ratio or "wear rate" (cumulative lost volume V or lost mass per sliding unit 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.

Notice that both coefficients refer to the softer material. In the present wear testing of pin-on-disc the softer material is the disc. The cumulative lost volume is obtained by,

$$V = m/\rho \qquad (m = \text{mass} \; ; \; \rho = \text{density}) \qquad (6)$$

Wear and friction are not exclusively material properties, but depend upon the process parameters. Thus, the definitive test for materials, coatings or lubricants should be in service application or in practice. The main advantage of bench testing simulation in the laboratory is the reduction in development costs and testing time. Another advantage is a better understanding of friction and the wear processes, eliminating materials which are not appropriate.

In order to simulate service conditions, laboratory testing must have the same real conditions as in service such as materials, contact pressure, temperature, humidity, environment, sliding velocity, friction power intensity and energy pulse. Friction coefficient for sliding or rolling is defined by,

$$\mu = \frac{F_t}{F_N} \tag{7}$$

where: F_N is the normal force and F_t is the tangential friction force.

3. EXPERIMENTAL PROCEDURE AND MATERIALS

The experimental results of the AISI 1005 steel discs and spheres of AISI 52100 steel were obtained by carrying out wear testing in the ball-on-disc equipment (Bressan at al., 2001), according to the ASTM G99 standard (ASTM, 1995; Williams, 1997). For each test, the selected constant total sliding distance was 3000 m and the normal loads on the ball were 1.96 N, 5.1 N, 7.1 N, 10 N, 15.1 N, 19 N and 29 N. Controlled room temperature and humidity were at 26 ^oC and 50 % respectively and the sliding velocity was also constant. Table 1 shows the utilized parameters during the testing operation. For each load, 2 disks were tested, i.e., a total of 14 disks.

Table 1- Parameters utilized for performing the ball-on-disc wear and friction tests.

Sliding velocity (m/s)	Load (N)	Total sliding distance (m)	Track radius (mm)
0.45	1.96 , 5.1 , 7.1 , 10 , 15.1 , 19 and 29	3000	14.5

3.1 Fabrication of Specimens

Ball. Comercial balls with 10 mm diameter of AISI 52100 steel balls either plasma nitrided or plasma nitrided coated with Al_2O_3 by MOCVD were used as the pin tip.

The Al_2O_3 coating was obtained via MOCVD (Metal Organic Chemical Vapor Deposition) by using aluminum dimethylisopropoxide as the precursor in a $N_2 + O_2 + H_2O$(vapor) controlled atmosphere; the reactor temperature was kept at 350°C while the precursor was evaporated at 0°C in an ice bath and carried into the reactor by 50 sccm N_2. The deposition was carried out for 30 min, giving rise to Al_2O_3 thicknesses of about 1.2 μm.

Discs. The counterface or disc was obtained by shearing and pré-machining AISI 1005 steel sheet, 2.88 mm thickness, 50 mm diameter and exhibiting an average Vickers micro-hardness of 120 HV0.5 and were tested as received. All disks were machined to this established dimensions and polished with emery paper grit 600.

In table 2, the Vickers micro-hardness (mHV), the diameter, the average roughness R_a and the average roughness R_t for each ball and disc are presented.

Table 2- Characteristics of balls and disc.

Specimen	Micro-Hardness	Diameter (mm)	Roughness R_a(μm)	Rt(μm)	Upper film thickness	Process Temperature
Ball 52100 substrate (as received)	360 mHV0.1	9.96			-	-
Ball 52100 plasma nitrided: $20\%N_2+80\%H_2$	560 mHV0.2	9.96			30 μm	500 ^oC
Ball 52100 plasma carbo-nitrided with					-	400 ^oC
white layer plus coating Al_2O_3	980 mHV0.025	9.96			1.2 μm	350 ^oC
Disc	120 mHV0.5	50 – 55	0.95	6.8	-	-

3.2 Procedure for Ball-on-disk Testing

The specimens were submitted to a rigorous preparation procedure to eliminate any trace of dust, dirt or oxidation. Next, the tribometer sliding track radius, the rotation velocity of disc and the revolution counter were set to the operation conditions for a sliding velocity of 0.45 m/s. The revolution counter was programmed to stop at each 200 m of sliding distance for the total of 3000 m, in order to allow intermediate measurements of pin with ball and disc lost mass and the worn area on the steel ball by a micrometer accurate to 0.002 mm. These measurements were always preceded by a complete cleaning of specimens by rubbing a dry cloth followed by using a flux of compressed air.

Then, pin with the 52100 steel ball and disc were weighed in an analytic balance with resolution 0.1 mg to determine its initial mass before testing. Before weighing, the discs were dried out in a furnace at 80ºC for 10 min to avoid any solvent or humidity in the specimen so as to evaluate the real lost mass from the disk. Pin and disk were fixed in the same position and orientation by an initial printed sign. The pin-on-disk apparatus was equipped with a large glass case that covered the specimens to control humidity. Temperature and humidity inside the campanula were kept at approximately 26 ºC and 40 % to 50 % of relative humidity. One type of normal load on the pin was selected for each test. The 1005 steel discs were tested on one face only. For each new disk, a new ball contact area was utilized by turning the ball in a new position inside the pin.

3.3 Tribometer Ball-on-disc

The automated ball-on-disc tribometer was developed and fabricated in the Tribology Laboratory of the Mechanical Engineering Department – UDESC and is seen in Fig. 1. Friction force measurements are transmitted to the computer through a load cell which supports the pin and the signal is processed by an electronic acquisition data plate. The 30 Kgf load cell measures the tangential force only. Friction force and friction coefficient is plotted in a on-line graph by the Labview programme. Disk rotation can vary from 80 to 1000 rpm which allows testing at 0.1 m/s to 2 m/s. Normal loads on the pin can vary from 1 N to 150 N.

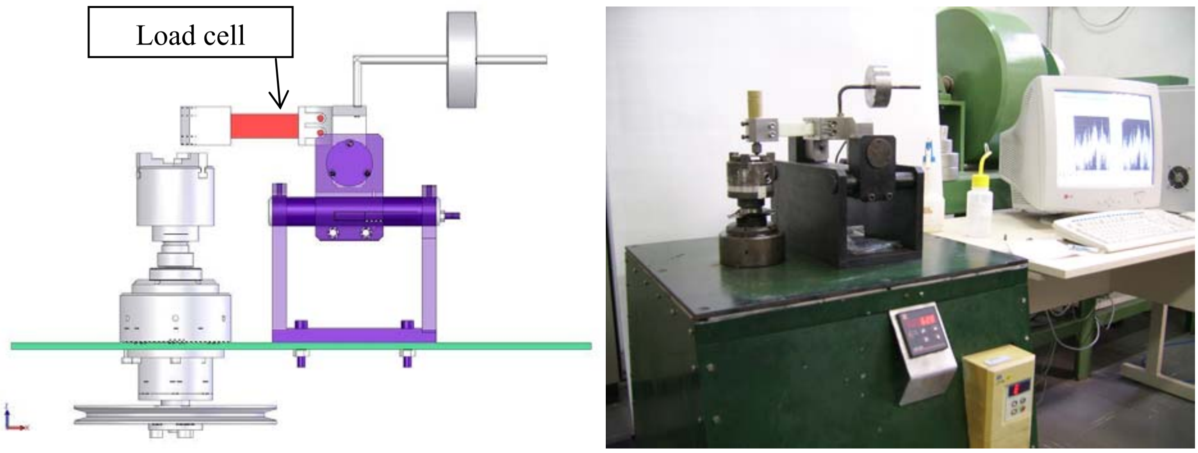

Figure 1. Sketch of Tribometer ball-on-disc and bench with computer for data acquisition.

4. RESULTS AND DISCUSSION

In Figs. 2 and 3, the micrographs obtained by SEM from the SAE 1005 steel disc surface with wear track and 52100 steel ball after sliding 50 m in the wear test are presented. The photos show the disc superficial wear track morphology and the formation of wear debris by a delamination mechanism and the ball worn contact area which is approximately an ellipse. These micro-chips or debris are pressed together by the ball to form the intermediary layer or adherence layer.

The calculated worn area of contact in the ball is obtained by the ellipse area formula and the nominal pressure in the ball worn contact area is calculated by,

$$P = \frac{F_N}{A} = \frac{F_N}{\frac{\pi}{4} d_1 d_2} \quad (8)$$

where d_1 and d_2 are the maximum and minimum ellipse diameters measured by an optical microscope equipped with a x-y table which had micrometers accurate to 0.002 mm. Nominal pressure evolution along the sliding distance in the ball-on-disc testing is shown in Figs .6 to 11.

In Fig. 4, the average friction coefficient in 2700 m versus the different normal loads for the 52100 steel ball plasma nitrided against 1005 steel disc is shown. Friction coefficient is approximately constant and is about 0.6 for loads varying from 1.96 N to 19 N. However, during ball-on-disc testing, the friction coefficient can vary from 0.6 to 1.3 as seen in Fig. 5 for normal load of 19 N. This is due to the wear mechanisms acting at different times: delamination, adhesion and intermediary layer formation. The high increase in the disc lost volume or the wear rate from 1600 m to 2400 m is possibly due to severe wear mechanisms by delamination and adhesion between disc and ball from the breakage of the ball's Al_2O_3 film and plasma nitrided layer which increases the friction coefficient from 0.6 to 1.3.

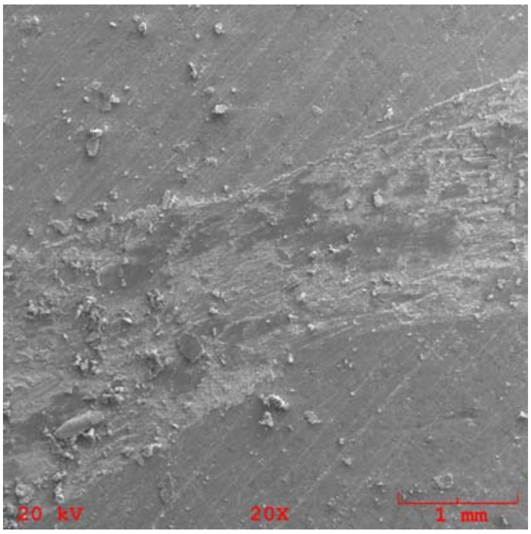

Figure 2. Formation of wear debris and the intermediary layer in the wear track of 1005 steel disc after 200 m sliding distance. 20x.

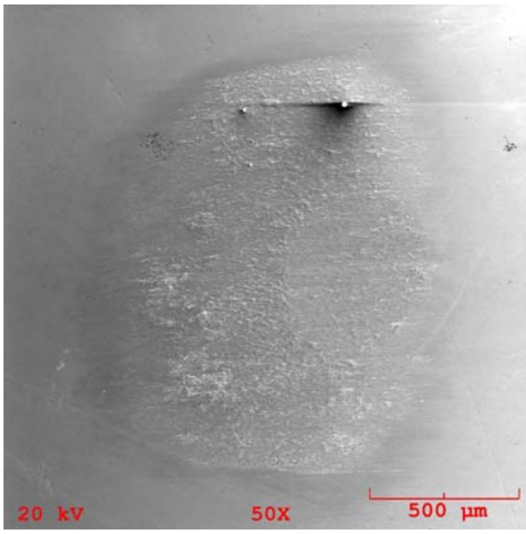

Figure 3. Ball worn area after 50 m sliding distance. Delamination and adhesion of debris from disc. 50x.

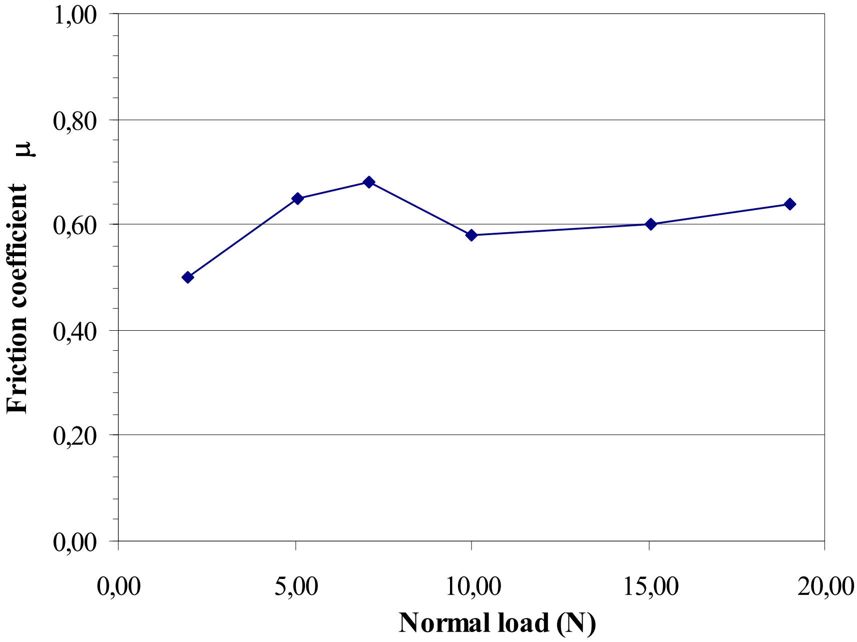

Figure 4. Average friction coefficient versus normal loads for 52100 steel ball plasma nitrided against AISI 1005 steel disc in ball-on-disc testing.

Figure 6 shows the nominal pressure variation during the ball-on-disc testing for a normal load of 19 N, according to eq. (9). Pressure decreases from 12.3 MPa to 2.3 MPa along the sliding distance of 200 m to 3000 m due to the increase in the ball worn contact area. The abrupt change of wear rate at 1600 m is due to breakage of Al_2O_3 film and plasma nitriding layer which increase wear. The graph shows also that below the pressure of 2.4 MPa, disc wear rate is almost zero.

The cumulative lost volumes of AISI 1005 steel disc and 52100 steel ball plasma nitrided versus sliding distance and nominal pressure versus sliding distance are presented in Fig. 7 for a very small normal load of 1.96 N: the nominal pressure decreases from the initial 10.5 MPa to 1.4 MPa at the final point. The lost volume curve for the disc shows two distinct wear regimes: an initial stage of high wear rate up to 300 m and the second stage or steady state wear of constant wear rate. Thus, although the nominal pressure decreases, the wear rate is constant from 300 m up to 2700 m. Disc 1 and disc 2 have different wear curves due to the ball hardness variations: softer balls yielded lower disc wear rate. In Fig. 8, the normal load was increased to 10 N which increased the initial contact pressure to 31 MPa for disc 7 and the final nominal pressure is 4 MPa. The nominal pressure for disc 8 is lower than disc 7, resulting in lower wear rate.

In Fig. 9, the normal load was increased further to 19 N which yielded a nominal initial pressure of 11 MPa and terminal pressure of 1.5 MPa. These are lower values than the nominal pressure for the normal load of 10 N and are due to the formation of a hard intermediary layer which modified the disc wear rate behavior. The measured friction coefficient was approximately constant at 0.7. A sharp increase in the wear rate occurred at 1600 m due to the breakage of the nitrided layer.

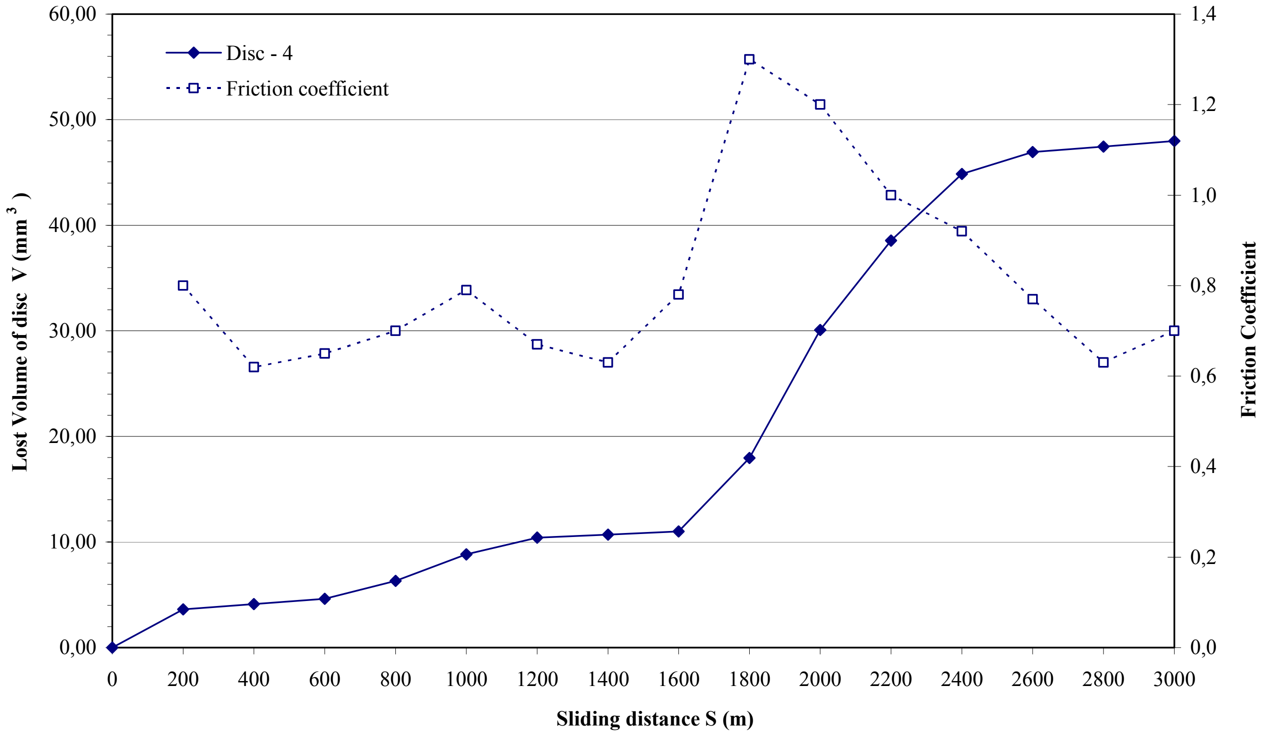

Figure 5. Average friction coefficient at each 200 m versus sliding distance for 52100 steel ball plasma carbo-nitrided plus coating Al_2O_3 against AISI 1005 steel disc in ball-on-disc testing. Also cumulative lost volume of 1005 steel disc. Normal load of 19 N. Sharp increase of wear rate at 1600 m: film breakage.

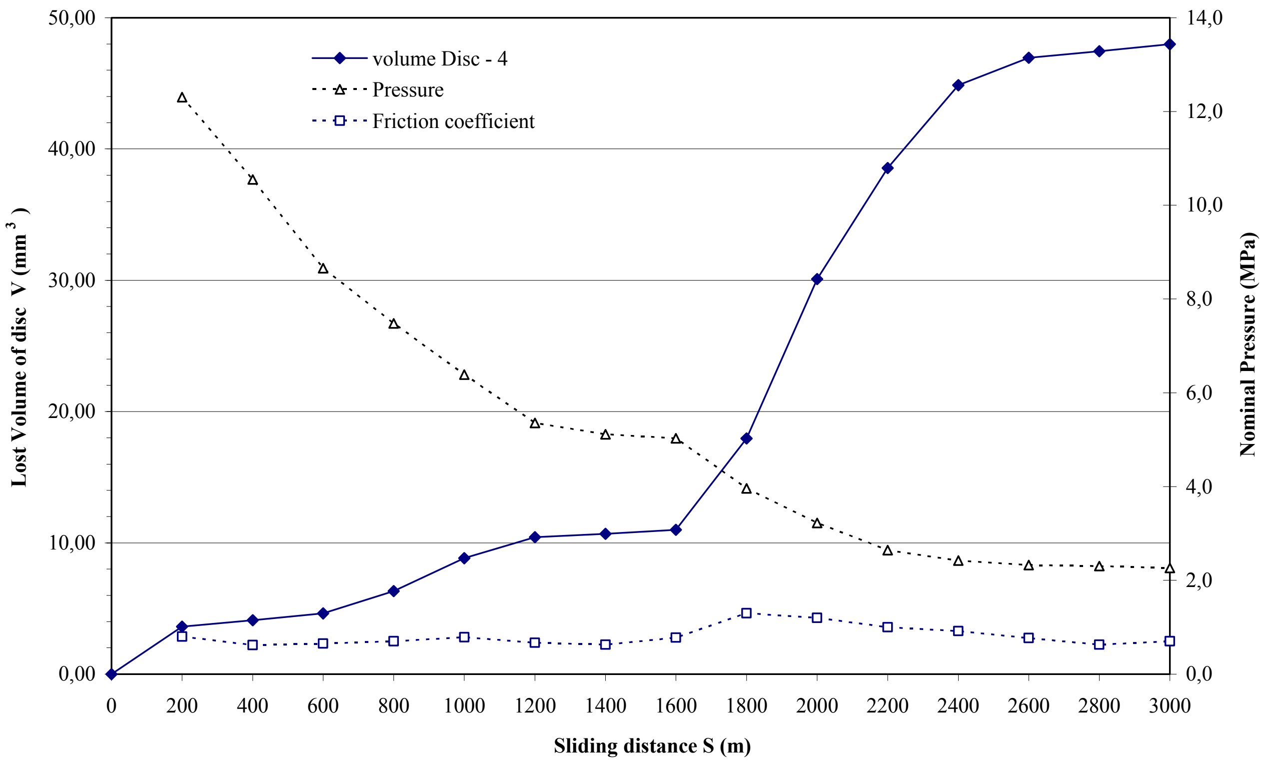

Figure 6. Average normal pressure at each 200 m versus sliding distance for 52100 steel ball plasma carbo-nitrided plus coating Al_2O_3 against AISI 1005 steel disc in ball-on-disc testing. Normal load of 19 N.

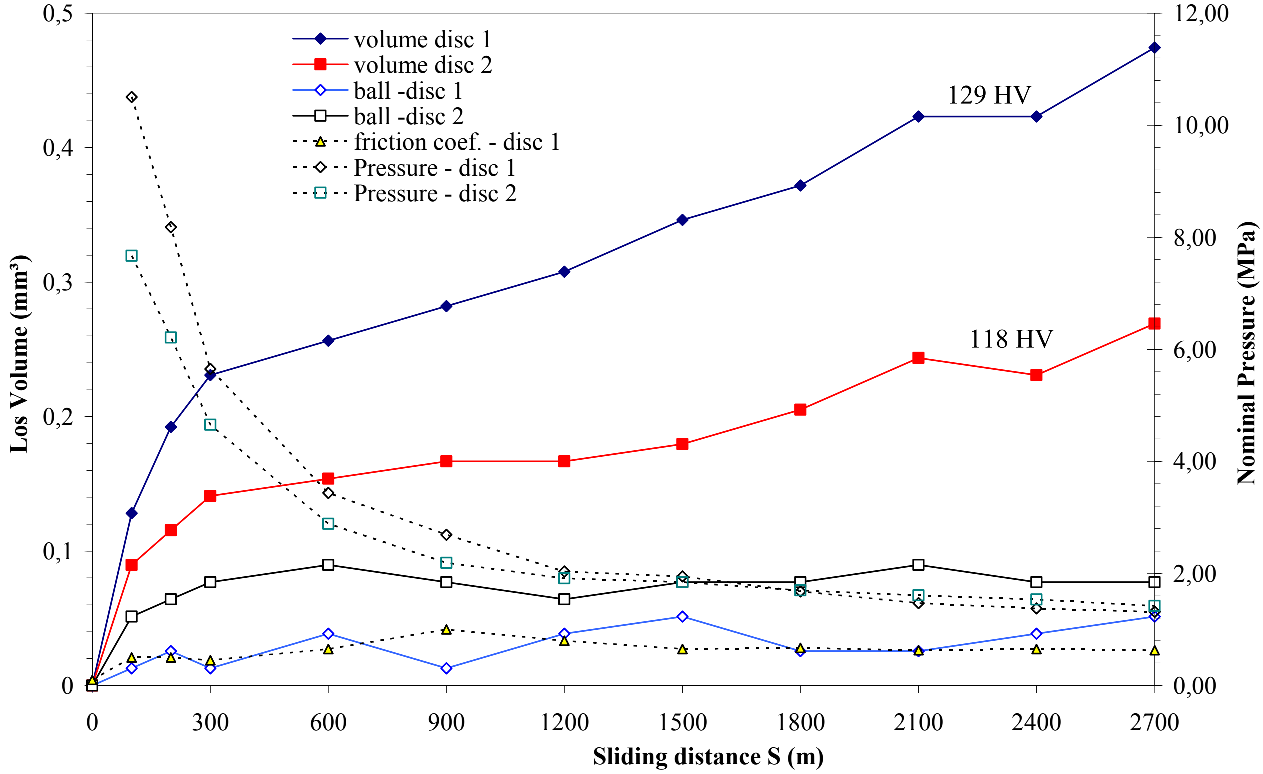

Figure 7. Cumulative Lost Volumes of AISI 1005 steel disc and 52100 steel ball plasma nitrided versus sliding distance and nominal pressure versus sliding distance. Normal load of 1.96 N.

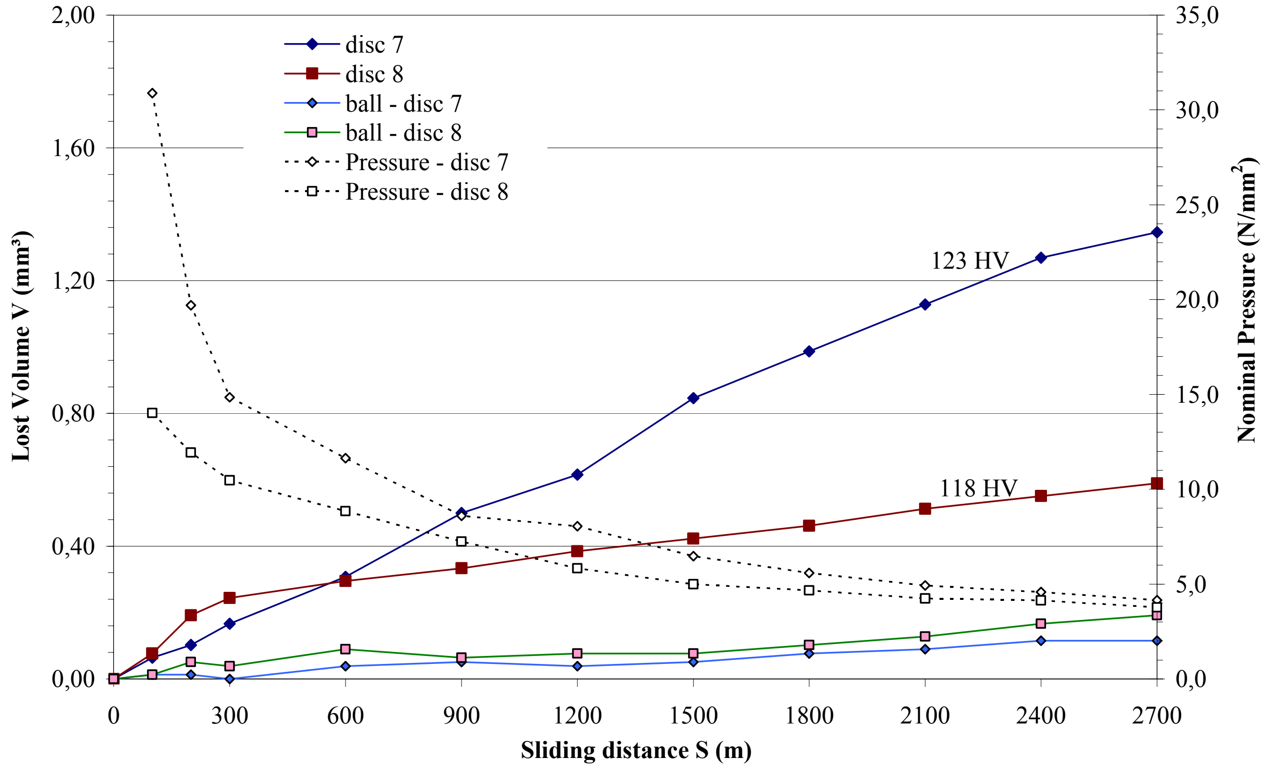

Figure 8. Cumulative Lost Volumes of AISI 1005 steel disc and 52100 steel ball plasma nitrided versus sliding distance and nominal pressure versus sliding distance. Normal load of 10 N.

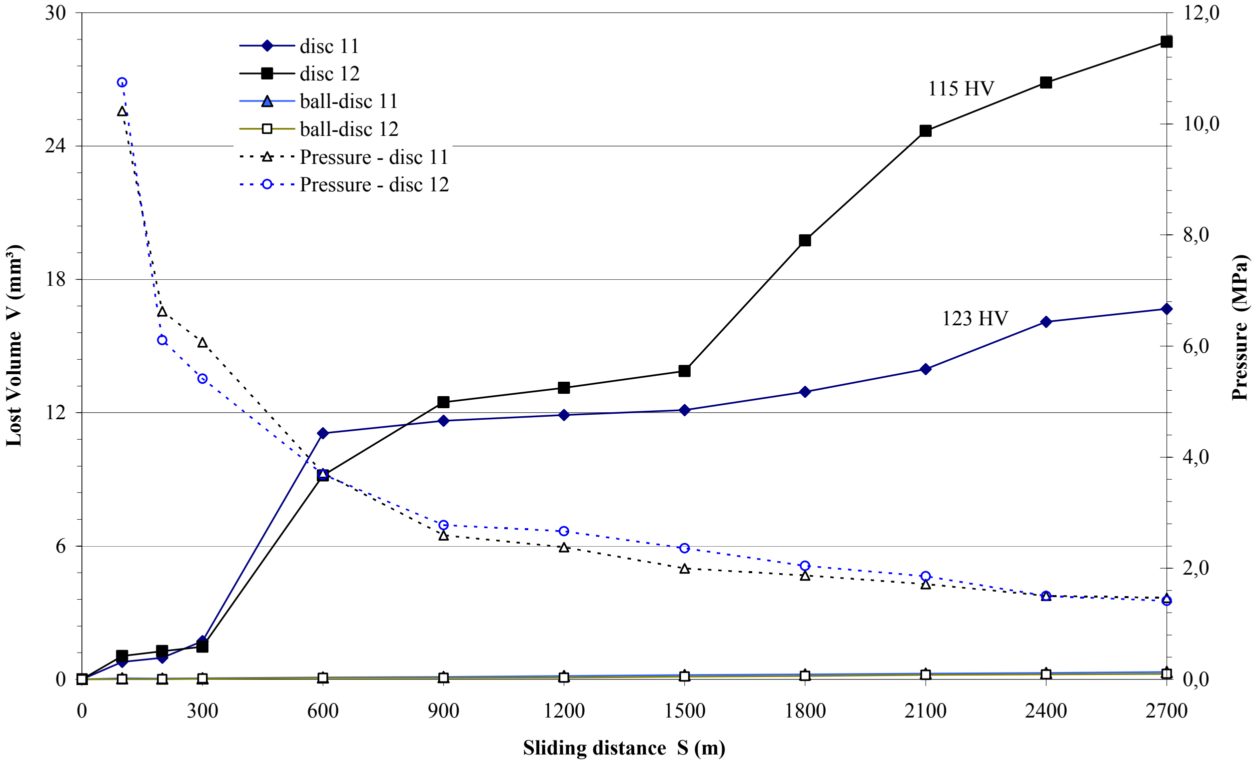

Figure 9. Cumulative Lost Volumes of Disc 1005 steel discs versus sliding distance and nominal pressure versus sliding distance. Ball of 52100 steel plasma nitrided. Normal load of 19 N.

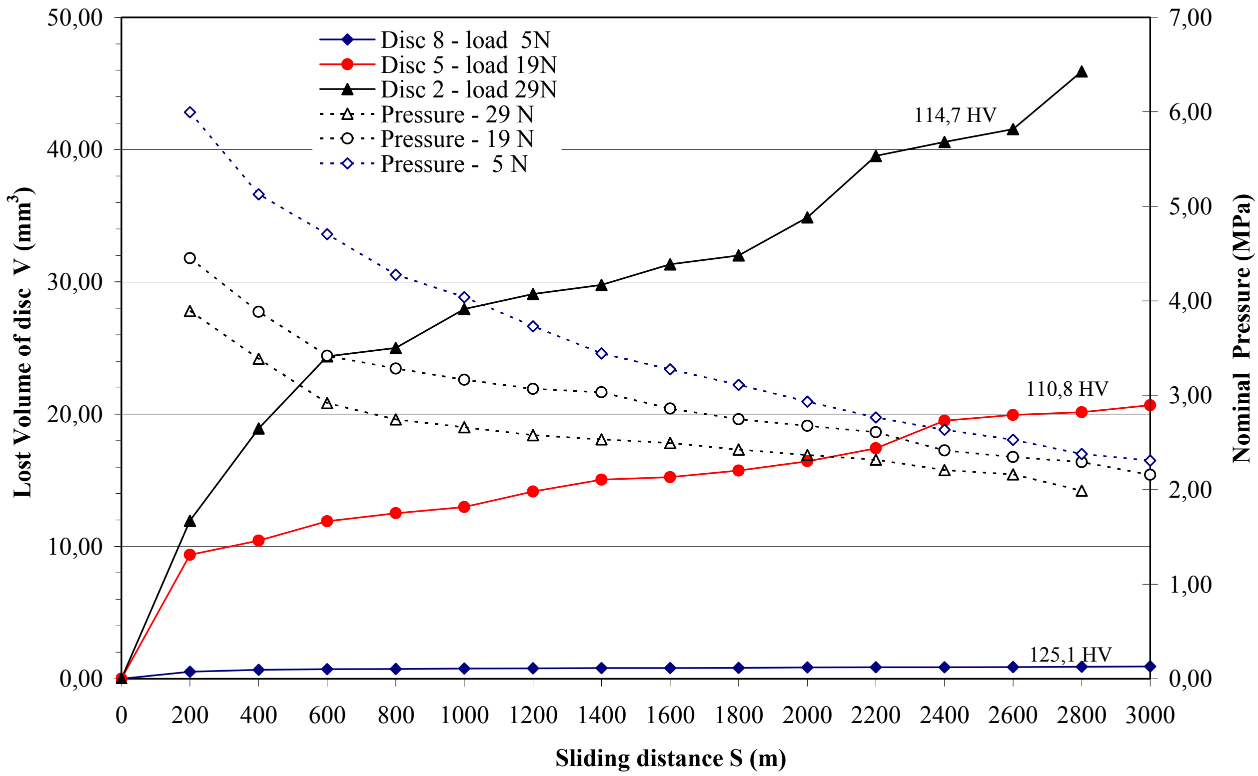

Figure 10. Cumulative lost volume of 1005 steel disc versus sliding distance and nominal pressure versus sliding distance. AISI 52100 steel ball plasma nitrided and coated with Al_2O_3. Normal loads of 5 N, 19 N and 29 N.

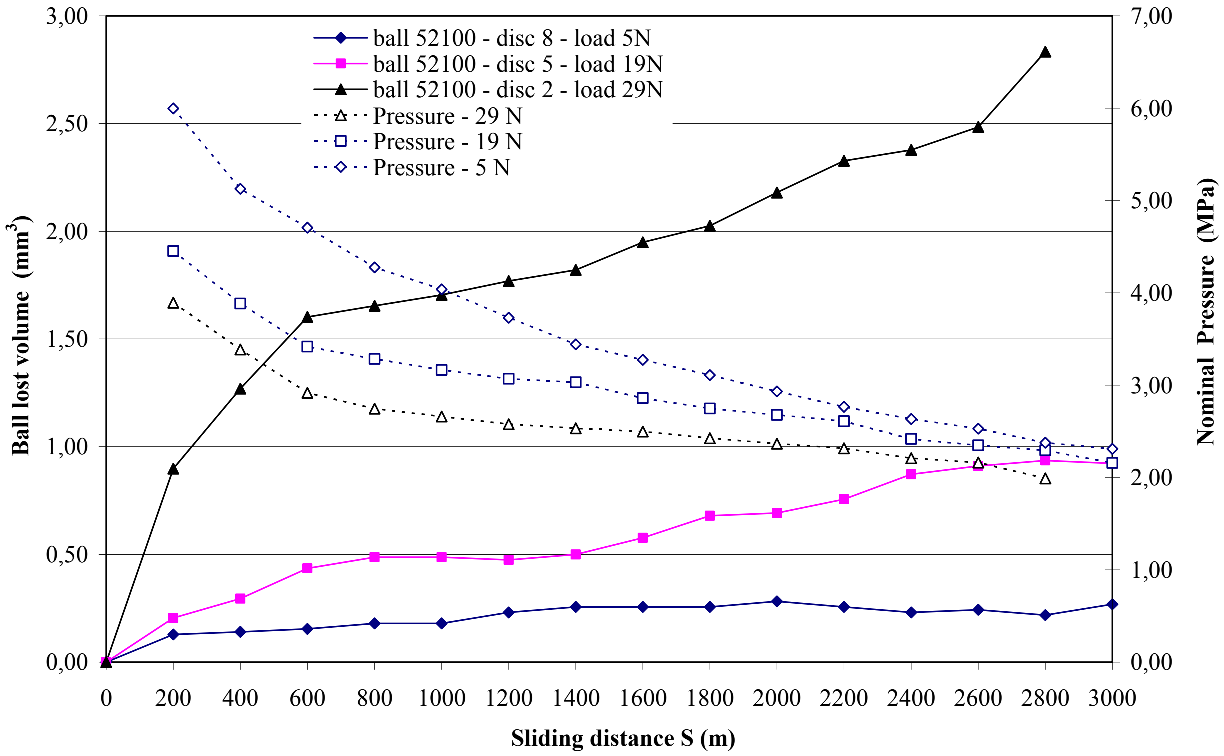

Figure 11. Cumulative lost volume of 52100 steel ball plasma nitrided and coated with Al_2O_3 versus sliding distance and nominal pressure versus sliding distance against 1005 steel disc. Normal loads 5 N, 19 N and 29 N.

In Figs. 10 and 11, the cumulative lost volumes of AISI 1005 steel disc and 52100 steel ball plasma nitrided and coated with Al_2O_3 versus sliding distances are investigated for increasing normal loads of 5 N, 19 N and 29 N. Wear rate increases with increasing normal load as expected. However, the nominal pressure obtained from the measured worn contact area in the ball and the normal load, eq. (8) is apparently lower than for steel balls plasma nitrided only, but pressure decreases to the final value of about 2 MPa as in Fig. 9. The wear behavior can be divided in two stages as before: the initial stage up to 600 m or “running in” phase of high wear rate and the second stage or steady state regime of a constant wear rate from 600 m to 3000 m. In the steady state regime, the lost volume is linear relative to the sliding distance. Therefore, from these experimental observations, the following equation is proposed for the total cumulative lost volume and wear rate in the second wear stage or steady state wear regime behavior of steel,

$$Q_s = \frac{V - V_o}{S - S_o} = K\frac{F_N}{H} \quad (9)$$

$$V = V_o + Q_s(S - S_o) = V_o + K\frac{F_N}{H}(S - S_o) \quad (10)$$

where Q_S is the parameter that measures the wear ratio or “wear rate” in the second stage or the steady state regime of wear , V is the total cumulative lost volume of disc material, V_o is the total lost volume in the initial stage of wear, S_o is sliding distance in the initial stage of wear or “running in” phase and K is the non-dimensional wear coefficient.

Figure 12 shows the cumulative lost volume of AISI 52100 steel ball plasma nitrided versus its worn contact area against discs of AISI 1005 steel for a wide range of normal loads: from 1.96 N up to 19 N. Ball lost volume is approximately linear proportional to its worn area as expected. However, the experimental results fall inside a band of points which implies that the wear coefficient K or the constant of proportionality has some variations, depending on the load and the ball surface film hardness.

5. CONCLUSIONS

From the experimental results of friction and wear behavior of AISI 52100 steel ball plasma nitrided and coated with Al_2O_3 sliding against AISI 1005 steel disc, the following conclusions can be drawn:

a)- The wear behavior can be divided in two stages: the initial stage up to 300 m or 600 m, depending on the material, or the “running in” phase of high wear rate and the second stage or the steady state wear regime of a constant wear rate from 600 m to 3000 m. In the steady state wear regime, the lost volume is linear relative to the sliding distance despite the decrease in the nominal pressure in the contact area between ball and disc.

b)- The nominal pressure obtained by dividing the normal load per measured worn contact area in the ball decreased from the initial value of 10.5 MPa to 1.4 MPa at the final point for a normal load of 1.96 N. A normal load of 19 N yielded similar nominal initial pressure of about 11 MPa and terminal pressure of 1.5 MPa.
c)- Wear rate depended on both disc and ball hardness, i.e., wear rate depended upon the difference of hardness of the material pair or on the effective hardness: $1/H_e = 1/H_b + 1/H_d$, where H_b is the ball hardness and H_d the disc hardness.
d)- An empirical equation is proposed for the total cumulative lost volume for ball-on-disc testing,

$$V = V_o + Q_s (S - S_o) = V_o + K \frac{F_N}{H} (S - S_o)$$

where V_o is the lost volume in the initial stage of wear and S_o is the sliding distance in the initial stage of wear or "running in" phase. Lost volume increases linearly with the normal load as observed.
e)- After the ball plasma nitrided layer and/or the coating film Al_2O_3 were removed, a sharp increase in the disc wear rate occurred at 1600 m due to the film breakage for a normal load of 19 N.
f)- The ball lost volume is approximately linearly proportional to its worn contact area as expected.
g)- The observed wear mechanism in both disc and ball are: micro-delamination, adhesion and formation of a hard intermediary layer from the wear debris which modified the disc wear rate behavior.

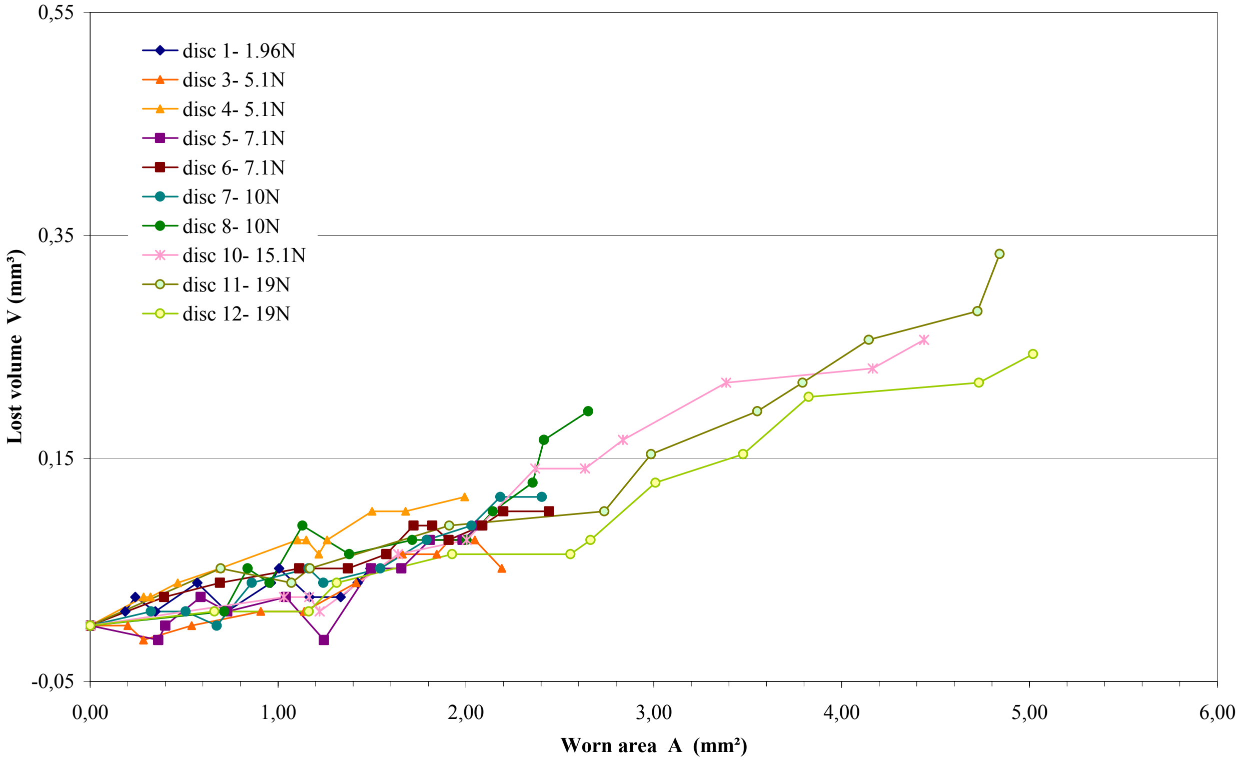

Figure 12. Cumulative lost volume of AISI 52100 steel ball plasma nitrided versus its worn contact area against discs of AISI 1005 steel for various loads.

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