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Study of the Influence of the Micro-Abrasive Wear Modes on the Behaviors of the Volume of Wear and Coefficient of Friction of Thin Films Submitted to Micro-Abrasive Wear

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ABSTRACT
The purpose of this work is to study the influence of the micro-abrasive wear modes on the behaviors of the volume of wear (V) and on the coefficient of friction (μ) of thin films. Experiments were conducted with thin films of TiN, TiAlN, TiN/TiAlN, TiHfC, ZrN and TiZrN, using a ball of AISI 52100 steel and abrasive slurries prepared with black silicon carbide (SiC) particles and glycerine. The results show that the abrasive slurry concentration affected the abrasive wear modes ("*grooving abrasion*" or "*rolling abrasion*") and, consequently, the magnitude of the volume of wear and of the coefficient of friction, as described: *i*) a low value of abrasive slurry concentration generated "*grooving abrasion*", which was relationed to a relatively low volume of wear and high coefficient of friction; *ii*) a high value of abrasive slurry concentration generated "*rolling abrasion*", which was relationed to a relatively high volume of wear and low coefficient of friction.
Keywords: Micro-abrasive wear, grooving abrasion, rolling abrasion, thin films, volume of wear, coefficient of friction.

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1. INTRODUCTION

The micro-abrasive wear test by rotative ball ("*ball-cratering wear test*") is an important method adopted to study the micro-abrasive wear behavior of metallic, polymeric and ceramic materials. Figure 1 presents a schematic diagram of the principle of this micro-abrasive wear test, in which a rotating ball is forced against the tested specimen in the presence of an abrasive slurry, generating, consequently, the called "*wear craters*" on the surface of the tested material.

Initially, the development of the ball-cratering wear test aimed to measure the thickness of thin films [1] using the equations detailed in Reference [2]. Because of the technical features, this type of micro-abrasive wear test has been applied to study the tribological behavior of different materials [3-5], for example, in the analysis of the volume of wear (V), coefficient of wear (k) and coefficient of friction (μ) of thin films [2,6-10].

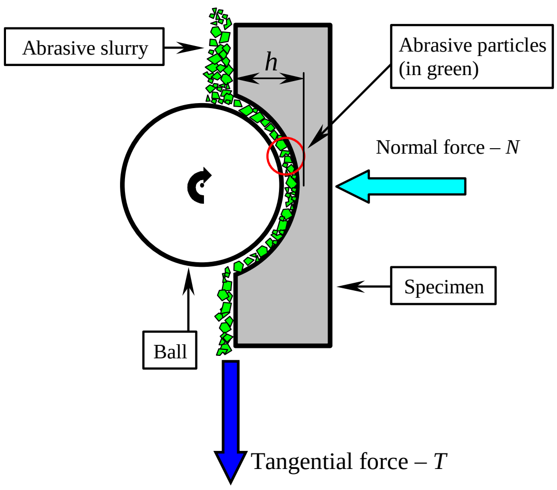

Figure 1: Micro-abrasive wear test by rotating ball: a representative figure showing the operating principle and the abrasive particles between the ball and the specimen. "h" is the depth of the wear crater.

As a function of the abrasive slurry concentration, two micro-abrasive wear modes can beusually observed on the surface of the worn crater: "*grooving abrasion*" is observed when the abrasive particles slide on the surface, whereas "*rolling abrasion*" results from abrasive particles rolling on the specimen's surface. Figures 2a [11] and 2b present, respectively, images of "*grooving abrasion*" and "*rolling abrasion*" micro-abrasive wear modes.

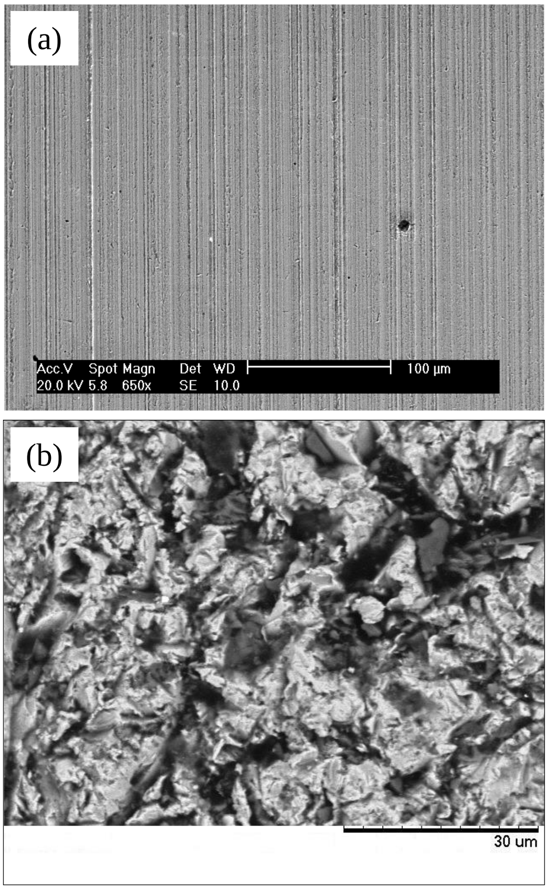

Figure 2: Micro-abrasive wear modes: (a) "*grooving abrasion*" [11] and (b) "*rolling abrasion*".

Analyzing and studying important researches regarding to tribological behavior of materials submitted to micro-abrasive wear tests conditions, the purpose of this work is to report the influence of the micro-abrasive wear modes on the behaviors of the volume of wear (V) and coefficient of friction (μ) of thin films submitted to micro-abrasive wear tests by rotative ball.

2. EQUIPMENT, MATERIALS AND METHODS

2.1 Ball-cratering wear test equipment

A ball-cratering wear test equipment with free-ball mechanical configuration (Figure 3) was used for the micro-abrasive wear tests, which has two load cells: one load cell to controll the "*normal force*" (N) and one load cell to measure the "*tangential force*" (T) that is developed during the experiments. The values of "N" and "T" are read by a readout system.

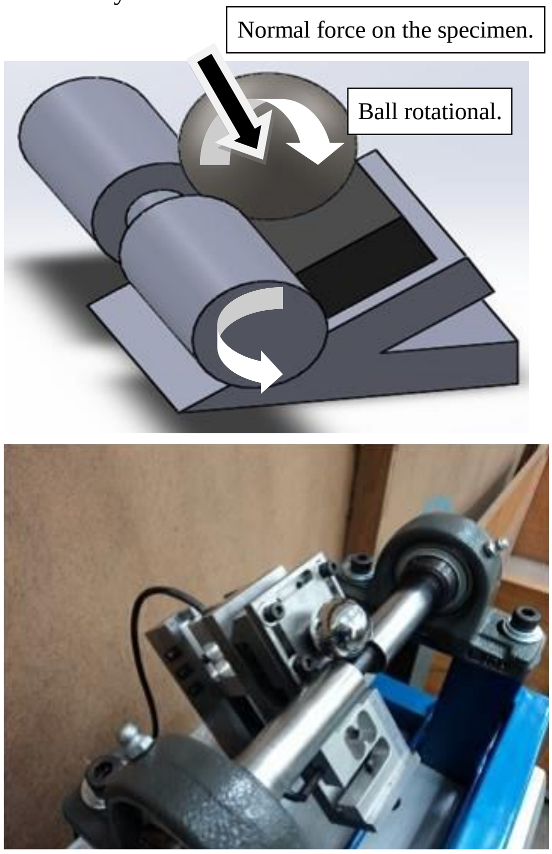

Figure 3: Ball-cratering micro-abrasive wear test equipment used in this work: free-ball mechanical configuration, able to acquisite, simultaneously, the "*normal force* – N" and the "*tangential force* – T".

2.2 Materials

Experiments were conducted with thin films of TiN, TiAlN, TiN/TiAlN, TiHfC, ZrN and TiZrN deposited on substrates of cemented carbide. For the counter-body, one ball of AISI 52100 steel with a diameter of D = 25.4 mm was used.

The abrasive material was black silicon carbide (SiC) with an average particle size of 3 µm. Figure 4 [4] presents a micrograph of the abrasive particles (Figure 4a) and the particle size distribution (Figure 4b). The abrasive slurries were prepared with SiC and glycerine.

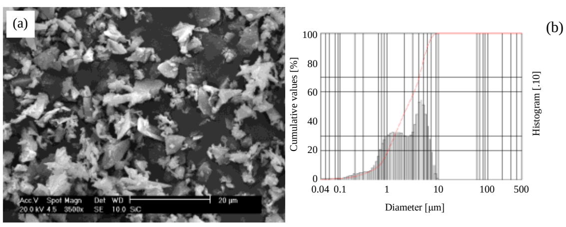

Figure 4: SiC abrasive [4]: (a) scanning electron micrograph and (b) particle size distribution.

2.3 Methods

Table 1 presents the values of the test parameters defined for the micro-abrasive wear experiments.

Table 1: Test parameters selected for the ball-cratering wear experiments.

Normal force	$N = 0.4$ N
Abrasive slurry concentration (in volume)	$C_1 = 5\%$ SiC + 95% glycerine
	$C_2 = 50\%$ SiC + 50% glycerine
Ball rotational speed	$n = 70$ rpm

The normal force value defined for the wear experiments was N = 0.4 *N*, combined with two abrasive slurries concentrations (*C*), $C_1 = 5\%$ SiC + 95% glycerine and $C_2 = 50\%$ SiC + 50% glycerine (volumetric values), with the purpose of to produce, respectively, "*grooving abrasion*" and "*rolling abrasion*" micro-abrasive wear modes. The ball rotational speed was set to $n = 70$ rpm.

All tests were *non-perforating*, e.g., only the thin films were worn. The normal force (*N*) was constant during the tests; the tangential force (*T*) was monitored and registered during all experiments.

The volume of wear (*V*) and the coefficient of friction (μ) were then calculated using Equations 1 [1] and 2, respectively; "*d*" is the diameter of the wear crater and "*R*" is the radius of the ball.

$$V \approx \frac{\pi d^4}{64R} \tag{1}$$

$$\mu = \frac{T}{N} \tag{2}$$

3. RESULTS AND DISCUSSION

Figure 5 shows examples of worn surfaces obtained in the experiments; in all wear craters, the maximum depth (*h*) observed was, approximately, $h \approx 8$ µm. Figure 5a displays the action of "*grooving abrasion*" micro-abrasive wear mode, characteristic of $C_1 = 5\%$ SiC + 95% glycerine; Figure 5b displays a wear crater under the action of "*rolling abrasion*" micro-abrasive wear mode, reported for the abrasive slurry concentration $C_2 = 50\%$ SiC + 50% glycerine. These results qualitatively agree with the conclusions obtained by Trezona *et al.* [12], in which low concentrations of abrasive slurries (< 5% in volume of abrasive material, approximately) favour "*grooving abrasion*" and high concentrations of abrasive slurries (> 20% in volume of abrasive material, approximately) favour the action of "*rolling abrasion*".

The actions of the abrasive wear modes showed an important influence on the volume of wear and on the coefficient of friction of the thin films studied in this research. A significant increase in the volume of abrasive particles from $C_1 = 5\%$ SiC + 95% glycerine to $C_2 = 50\%$ SiC + 50% glycerine (causing, consequently, the transition from "*grooving abrasion*" to "*rolling abrasion*"), caused an increase in the volume of wear and a decrease in the coefficient of friction.

Figures 6 and 7 show the behaviors of the volume of wear (*V*) and coefficient of friction (μ) as a function of the micro-abrasive wear modes (*C*); the maximum errors observed were 3.54×10^{-3} mm^3 and 0.11, for the volume of wear and coefficient of friction, respectively.

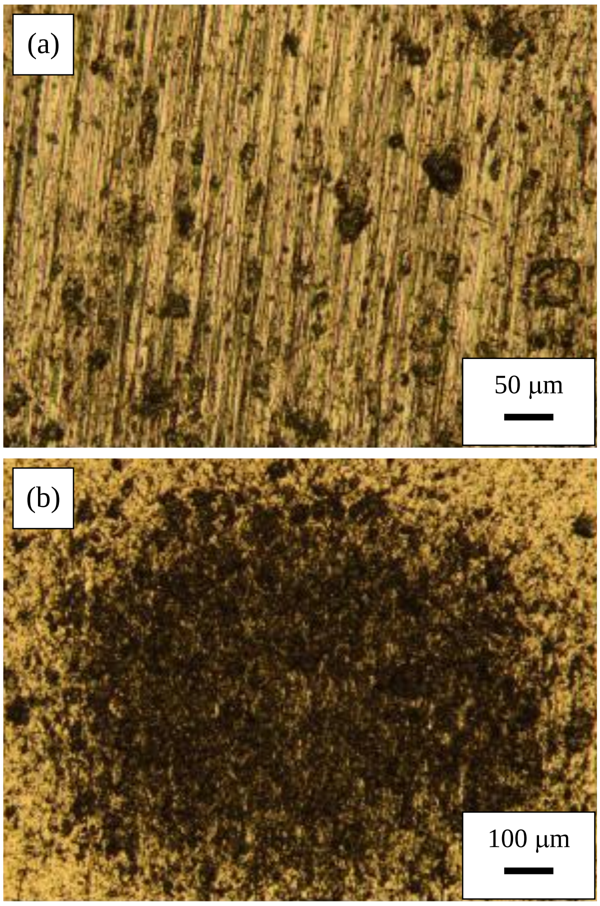

Figure 5: Occurrence of (a) "*grooving abrasion*" and (b) "*rolling abrasion*" on the surface of the TiN thin film.

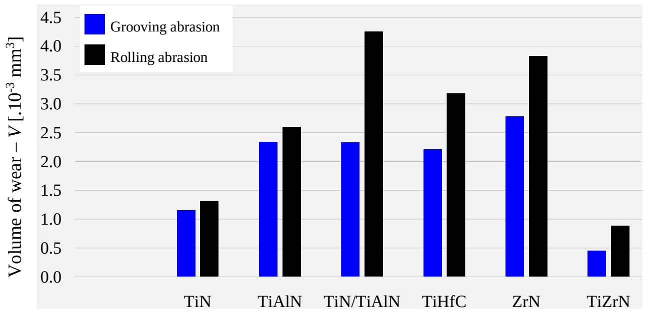

Figure 6: Volume of wear (*V*) as a function of the micro-abrasive wear modes. Maximum error of *V*: 3.54×10^{-3} mm^3.

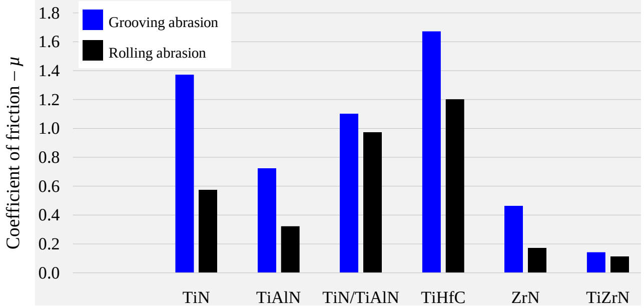

Figure 7: Coefficient of friction (μ) as a function of the micro-abrasive wear modes. Maximum error of μ: 0.11.

The values of the volume of wear reported under conditions of "*rolling abrasion*" (high abrasive slurry concentration – C_2 = 50% SiC + 50% glycerine) were higher than the values of the volume of wear reported under conditions of "*grooving abrasion*" (low abrasive slurry concentration – C_1 = 5% SiC + 95% glycerine), as reported by Mergler and Huis in 't Veld [5] and Trezona *et al.* [12].

The values of the coefficient of friction reported under "*grooving abrasion*" (low abrasive slurry concentration – C_1 = 5% SiC + 95% glycerine) were higher than the values of the coefficient of friction reported under "*rolling abrasion*" (high abrasive slurry concentration – C_2 = 50% SiC + 50% glycerine) and this behavior can be explained based on patterns of movements that act on "*rolling abrasion*" and "*grooving abrasion*" micro-abrasive wear modes: in "*rolling abrasion*" micro-abrasive wear mode, the abrasive particles are free to roll between the ball and the specimen, facilitating the relative movement between these elements and consequently decreasing the coefficient of friction on the tribological system; however, in "*grooving abrasion*" micro-abrasive wear mode, the abrasive particles are fixed on the counter-body (in this case, on the ball), limiting their movements and requiring higher tangential forces.

4. CONCLUSIONS

The results obtained in this work indicated the following:

- About the actions of the "*micro-abrasive wear modes*".
  (1) The concentration of abrasive slurry affected the occurrence of "*grooving abrasion*" or "*rolling abrasion*", as predicted by the literature [12];
  (2) With the low concentration of the abrasive slurry (C_1 = 5% SiC + 95% glycerine), it was produced "*grooving abrasion*" micro-abrasive wear mode on the surfaces of the thin films;
  (3) With the high concentration of the abrasive slurry (C_2 = 50% SiC + 50% glycerine), it was produced "*rolling abrasion*" micro-abrasive wear mode on the surfaces of the thin films.

- About the "*volume of wear – V*".
  (4) The volume of wear increased with the increase of the abrasive slurry concentration (from "C_1 = 5% SiC + 95% glycerine" to "C_2 = 50% SiC + 50% glycerine").

- About the "*coefficient of friction – μ*".
  (5) With the low concentration of abrasive slurry (C_1 = 5% SiC + 95% glycerine), "*grooving abrasion*" and, consequently, high values of coefficient of friction were reported. In this situation, the abrasive particles were incrusted on the counter-body, hindering their movements and generating high tangential forces;
  (6) However, when a high concentration of abrasive slurry (C_2 = 50% SiC + 50% glycerine) was used, "*rolling abrasion*" occurred. In this case, the abrasive particles were free to roll along the surface of the thin film, causing a low coefficient of friction.

5. ACKNOWLEDGEMENTS

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APPENDIX

A list of symbols used in this manuscript is given.

C	Abrasive slurry concentration – in volume [% SiC + % glycerine]	
d	Diameter of the wear crater	[mm]
D	Diameter of the ball	[mm]
h	Depth of the wear crater	[µm]
k	Coefficient of wear	[mm^3/N.m]
n	Ball rotational speed	[rpm]
N	Normal force	[N]
R	Radius of the ball	[mm]
T	Tangential force	[N]
V	Volume of wear	[mm^3]

Greek letter

µ Coefficient of friction

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