TRIBOLOGICAL BEHAVIOR OF THIN FILMS SUBMITTED TO MICRO-ABRASIVE WEAR

Marcelo de Matos Macedo[1], Jorge Thiago de Sousa Lima Wilcken[2] and Ronaldo Câmara Cozza[2,3*]

1 – Department of Materials Science, Federal University of ABC (UFABC), Santo André, SP.
2 – Department of Mechanical Engineering, University Center FEI – Educational Foundation of Ignatius "Padre Sabóia de Medeiros" (FEI), Av. Humberto de Alencar Castelo Branco, 3972 – 09850-901, São Bernardo do Campo, SP.
3 – Department of Mechanical Manufacturing, CEETEPS – State Center of Technological Education "Paula Souza", Faculty of Technology – FATEC-Mauá, Mauá, SP.
rcamara@fei.edu.br, ronaldo.cozza@fatec.sp.gov.br

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 of the coefficient of friction (μ) of thin films submitted to micro-abrasive wear. 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 micro-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, micro-abrasive wear modes, grooving abrasion, rolling abrasion, thin films.*

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)] (Figures 2a and 2b) 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)].
As a function of the abrasive slurry concentration, two micro-abrasive wear modes can be usually 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 3a[11,12] and 3b present, respectively, images of "*grooving abrasion*" and "*rolling abrasion*".

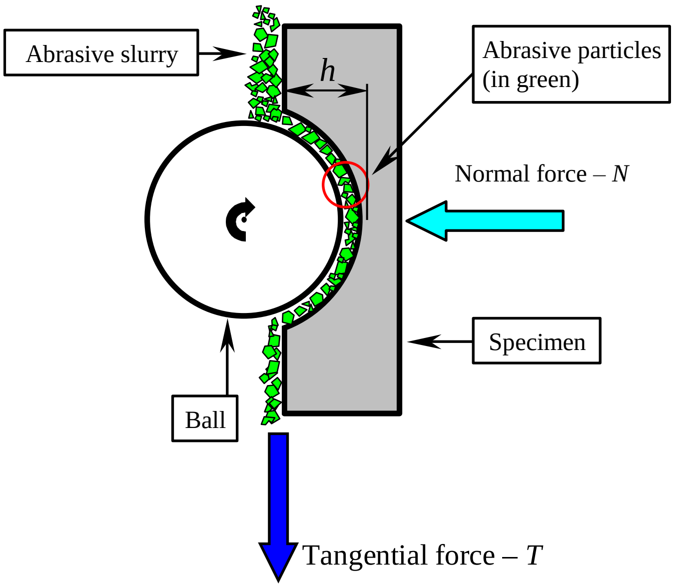

Figure 1: Micro-abrasive wear test by rotating ball: a representative figure showing the operating principle and the abrasive particles between the ball and the specimen; "*h*" is the depth of the wear crater.

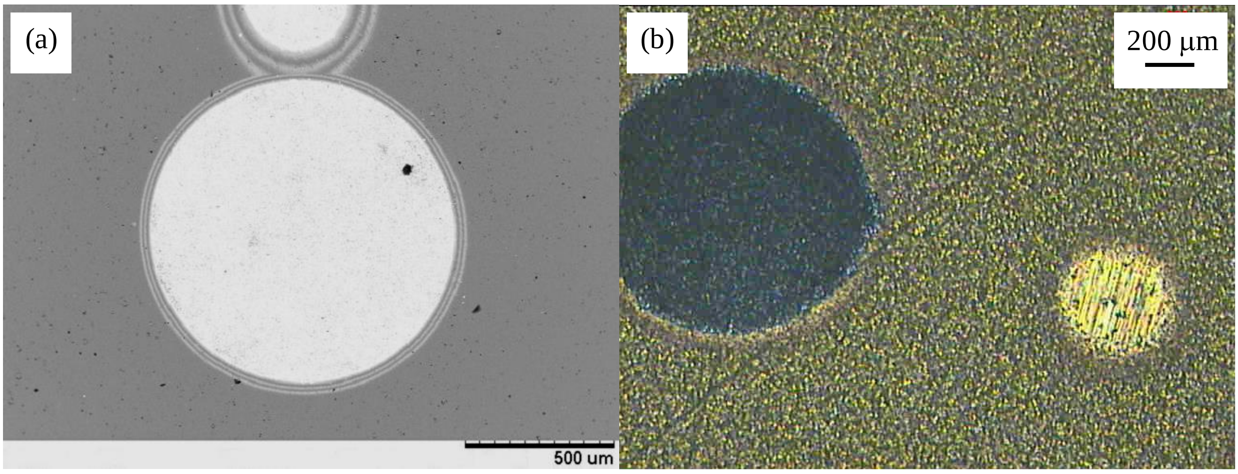

Figure 2: Examples of wear craters generated on coated system: (a) multi-layer and (b) thin film of TiN.

Analyzing and studying important researches regarding to tribological behavior of materials submitted to micro-abrasive wear tests conditions[7-9,13], 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.

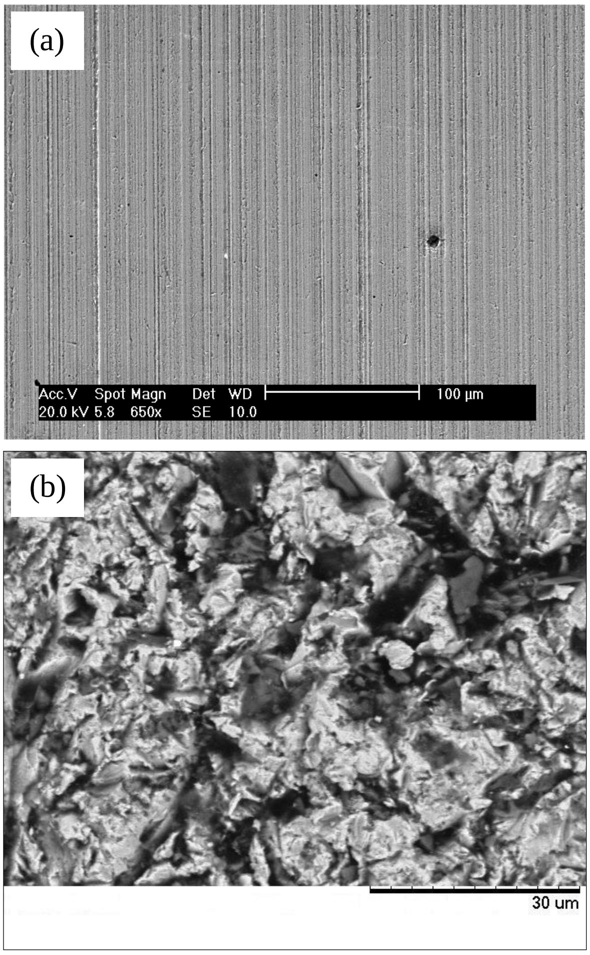

Figure 3: Micro-abrasive wear modes: (a) "*grooving abrasion*"[11,12] and (b) "*rolling abrasion*".

EQUIPMENT, MATERIALS AND METHODS

Ball-cratering wear test equipment

A ball-cratering wear test equipment with free-ball mechanical configuration (Figure 4[14]) 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.

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, was used one ball of AISI 52100 steel with diameter of D = 25.4 mm (D = 1" – standard size).
The abrasive material was black silicon carbide (SiC) with an average particle size of 3 µm; Figure 5[4] presents a micrograph of the abrasive particles (Figure 5a) and the particle size distribution (Figure 5b). The abrasive slurries were prepared with SiC and glycerine.

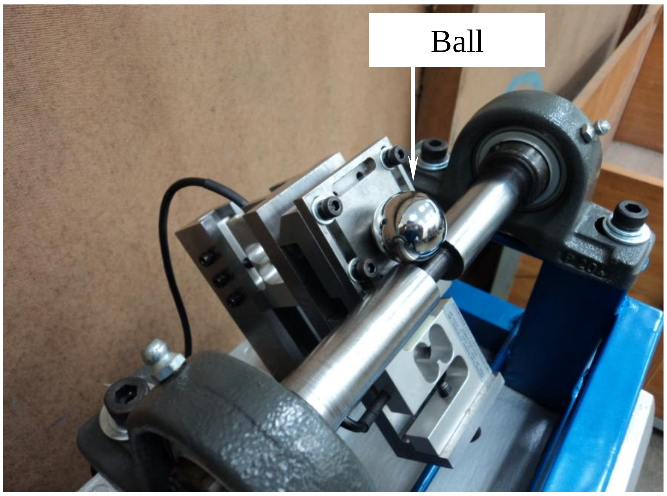

Figure 4: Ball-cratering micro-abrasive wear test equipment used in this work: free-ball mechanical configuration, able to acquisite, simultaneously, the "*normal force – N*" and the "*tangential force – T*".

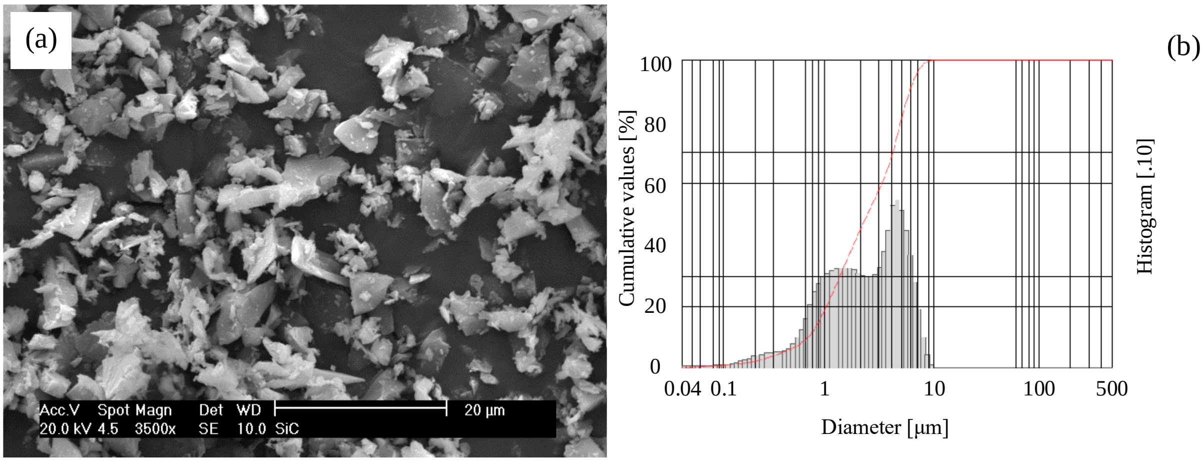

Figure 5: SiC abrasive[(4)]: (a) scanning electron micrograph and (b) particle size distribution.

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]	*N*	0.4
Abrasive slurry concentration (in volume)	C_1	5% SiC + 95% glycerine
	C_2	50% SiC + 50% glycerine
Ball rotational speed [rpm]	*n*	70

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*" on the surfaces of the thin films. 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 A[(1)] and B, respectively; "d" is the diameter of the wear crater and "R" is the radius of the ball.

$$V \cong \frac{\pi d^4}{64R} \qquad \text{(A)}$$

$$\mu = \frac{T}{N} \qquad \text{(B)}$$

RESULTS AND DISCUSSION

Figure 6 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 6a displays the action of "*grooving abrasion*", characteristic of C_1 = 5% SiC + 95% glycerine; Figure 6b displays a wear crater under the action of "*rolling abrasion*", reported for the abrasive slurry concentration C_2 = 50% SiC + 50% glycerine. These results qualitatively agree with the conclusions obtained by Trezona *et al.*[(15)], in which low concentrations of abrasive slurries (< 5% in volume of abrasive material, approximately) favor the occurrence of "*grooving abrasion*" and high concentrations of abrasive slurries (> 20% in volume of abrasive material, approximately) favor the action of "*rolling abrasion*".

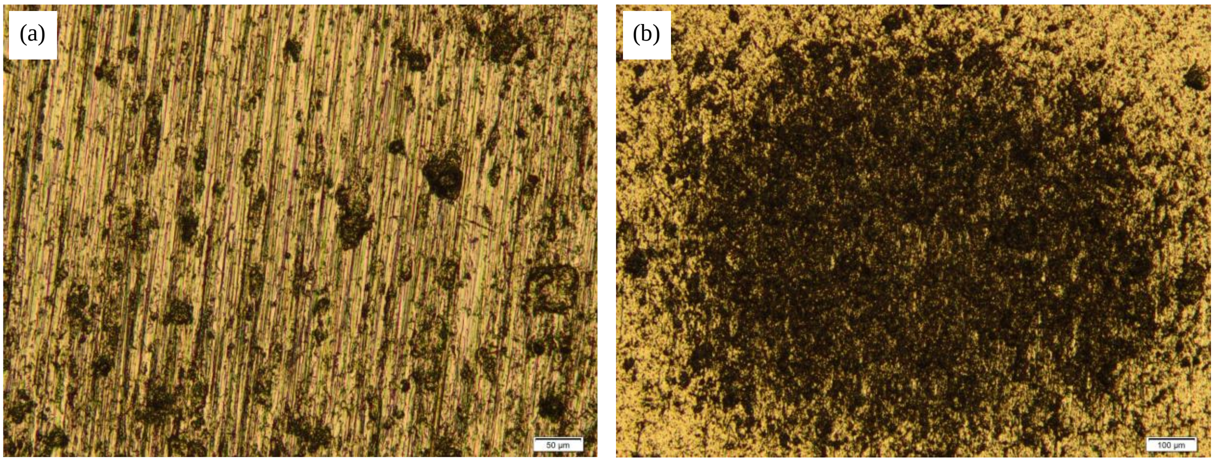

Figure 6: Occurrence of (a) "*grooving abrasion*" and (b) "*rolling abrasion*" on the surface of the thin film of TiN.

The actions of the micro-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 micro-abrasive wear transition from "*grooving abrasion*" to "*rolling abrasion*"), caused an increase in the volume of wear and a decrease in the coefficient of friction.

Figures 7 and 8 show the behaviors of the volume of wear (V) and coefficient of friction (μ) as a function of the micro-abrasive wear modes; the maximum errors observed were $V = 0.4 \times 10^{-3}$ mm^3 and $\mu = 0.1$, for the volume of wear and coefficient of friction, respectively.

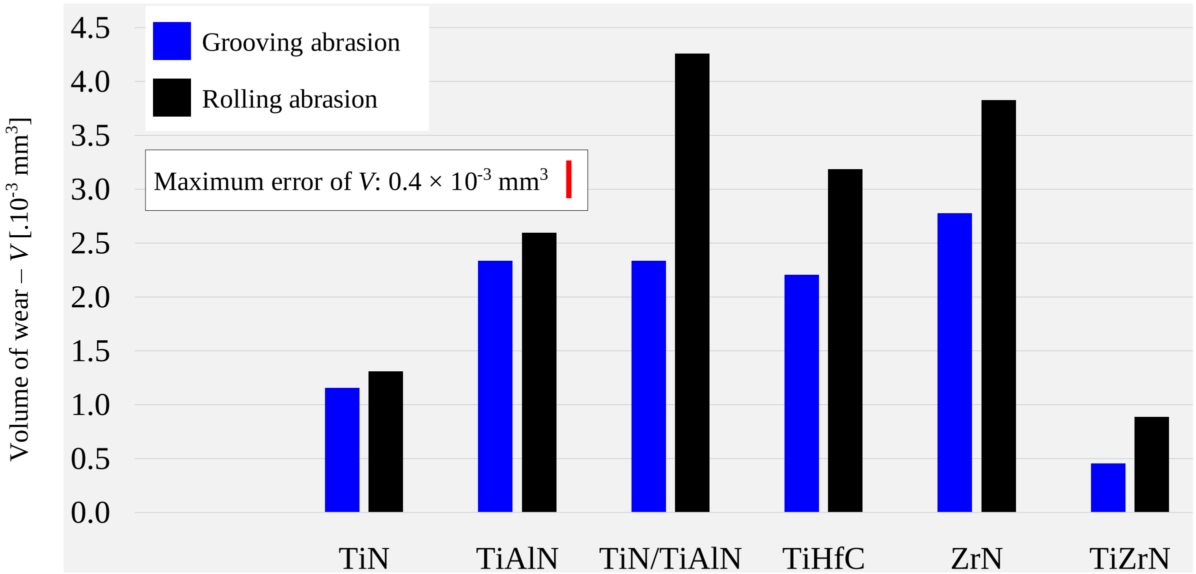

Figure 7: Volume of wear (V) as a function of the micro-abrasive wear modes "*grooving abrasion*" and "*rolling abrasion*".

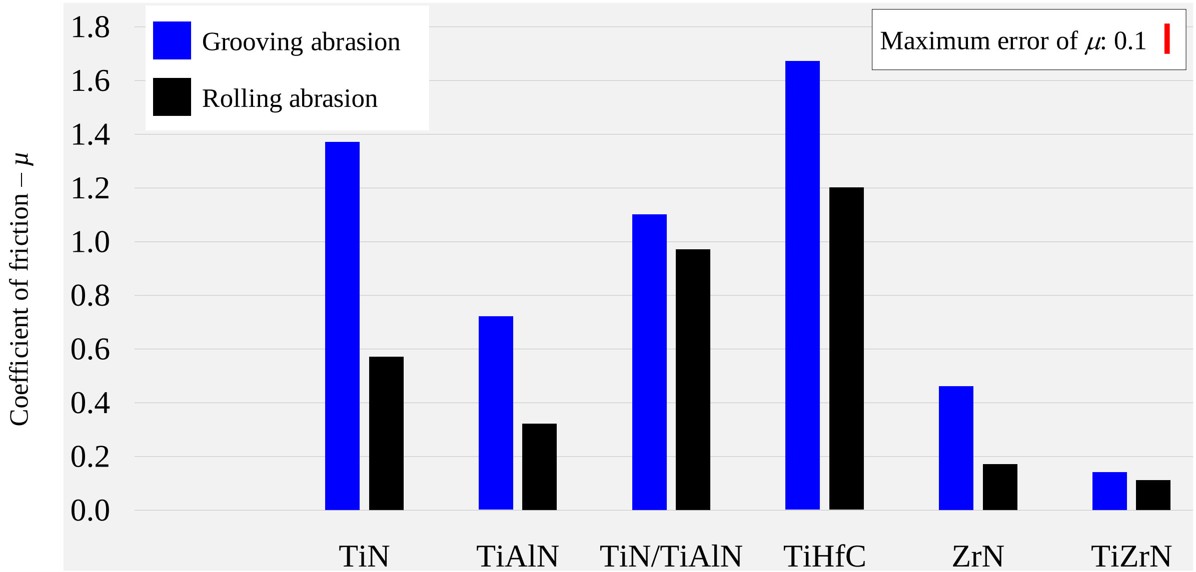

Figure 8: Coefficient of friction (μ) as a function of the micro-abrasive wear modes "*grooving abrasion*" and "*rolling abrasion*".

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.*[15].

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*", 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*", the abrasive particles are fixed on the counter-body (in this case, on the ball), limiting their movements and requiring higher tangential forces.

CONCLUSIONS

The results obtained in this work indicated the conclusions listed below.

(1) The concentration of abrasive slurry affected the occurrence of "*grooving abrasion*" or "*rolling abrasion*", as predicted by the literature[15];
(2) With the low concentration of the abrasive slurry (C_1 = 5% SiC + 95% glycerine), it was produced "*grooving abrasion*" 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*" on the surfaces of the thin films;
(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);
(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) In other hand, when the 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.

AKNOWLEDGEMENTS

Prof. Dr. Ronaldo Câmara Cozza gratefully acknowledges FAPESP – São Paulo Research Support Foundation, for the full financial support through Project Number 2019/01183-8 for the poster presentation of this paper at the "CBECiMat 2022 – 24º Congresso Brasileiro de Engenharia e Ciência dos Materiais.

REFERENCES

(1) RUTHERFORD, K.L.; HUTCHINGS, I.M. Theory and application of a micro-scale abrasive wear test. Journal of Testing and Evaluation – JTEVA, v. 25, n. 2, p. 250-260, 01 March 1997.
https://doi.org/10.1520/JTE11487J

(2) COZZA, R.C. A study on friction coefficient and wear coefficient of coated systems submitted to micro-scale abrasion tests. Surface and Coatings Technology, v. 215, p. 224-233, 25 January 2013.
https://doi.org/10.1016/j.surfcoat.2012.06.088

(3) COZZA, R.C.; TANAKA, D.K.; SOUZA, R.M. Friction coefficient and abrasive wear modes in ball-cratering tests conducted at constant normal force and constant pressure – Preliminary results. Wear, v. 267, n. 1-4, p. 61-70, 15 June 2009.
https://doi.org/10.1016/j.wear.2009.01.055

(4) COZZA, R.C.; RODRIGUES, L.C.; SCHÖN, C.G. Analysis of the micro-abrasive wear behavior of an iron aluminide alloy under ambient and high-temperature conditions. Wear, v. 330-331, p. 250-260, May-June 2015.
https://doi.org/10.1016/j.wear.2015.02.021

(5) MERGLER, Y.J.; HUIS IN 'T VELD, A.J. Micro-abrasive wear of semi-crystalline polymers. Tribological Research and Design for Engineering Systems, v. 41, p. 165-173, 2003.
https://doi.org/10.1016/S0167-8922(03)80129-3

(6) COZZA, R.C.; TANAKA, D.K.; SOUZA, R.M. Micro-abrasive wear of DC and pulsed DC titanium nitride thin films with different levels of film residual stresses. Surface and Coatings Technology, v. 201, n. 7, p. 4242-4246, 20 December 2006.
https://doi.org/10.1016/j.surfcoat.2006.08.044

(7) BATISTA, J.C.A.; GODOY, C.; MATTHEWS, A. Micro-scale abrasive wear testing of duplex and non-duplex (single-layered) PVD (Ti,Al)N, TiN and Cr-N coatings. Tribology International, v. 35, n. 6, p. 363-372, June 2002.
https://doi.org/10.1016/S0301-679X(02)00017-8

(8) SCHIFFMANN, K.I.; BETHKE, R.; KRISTEN, N. Analysis of perforating and non-perforating micro-scale abrasion tests on coated substrates. Surface and Coatings Technology, v. 200, n. 7, p. 2348-2357, 21 December 2005.
https://doi.org/10.1016/j.surfcoat.2005.01.015

(9) KUSANO, Y.; VAN ACKER, K.; HUTCHINGS, I.M. Methods of data analysis for the micro-scale abrasion test on coated substrates. Surface and Coatings Technology, v. 183, n. 2-3, p. 312-327, 24 May 2004.
https://doi.org/10.1016/j.surfcoat.2003.10.010

(10) RUTHERFORD, K.L.; HUTCHINGS, I.M. A micro-abrasive wear test, with particular application to coated systems. Surface and Coatings Technology, v. 79, n. 1-3, p. 231-239, February 1996.
https://doi.org/10.1016/0257-8972(95)02461-1

(11) COZZA, R.C. Influence of the normal force, abrasive slurry concentration and abrasive wear modes on the coefficient of friction in ball-cratering wear tests. Tribology International, v. 70, p. 52-62, February 2014.
https://doi.org/10.1016/j.triboint.2013.09.010

(12) COZZA, R.C. Third abrasive wear mode: is it possible? Journal of Materials Research and Technology, v. 3, n. 2, p. 191-193, April-June 2014.
https://doi.org/10.1016/j.jmrt.2014.03.010

(13) BATISTA, J.C.A.; JOSEPH, M.C.; GODOY, C.; MATTHEWS; A. Micro-abrasion wear testing of PVD TiN coatings on untreated and plasma nitrided AISI H13 steel. Wear, v. 249, n. 10-11, p. 971-979, November 2001. https://doi.org/10.1016/S0043-1648(01)00833-X
(14) COZZA, R.C. Effect of sliding distance on abrasive wear modes transition. Journal of Materials Research and Technology, v. 4, n. 2, p. 144-150, April-June 2015. https://doi.org/10.1016/j.jmrt.2014.10.007
(15) TREZONA, R.I.; ALLSOPP, D.N.; HUTCHINGS, I.M. Transitions between two-body and three-body abrasive wear: influence of test conditions in the microscale abrasive wear test. Wear, v. 225-229, Part 1, p. 205-214, April 1999. https://doi.org/10.1016/S0043-1648(98)00358-5

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	[$.10^{-3}$ mm^3]

Greek letter

μ	Coefficient of friction