

THIN FILMS: INFLUENCE OF THE MICRO-ABRASIVE WEAR MODES ON THE VOLUME OF WEAR AND COEFFICIENT OF FRICTION

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Abstract. The purpose of this research was to study the influence of the micro-abrasive wear modes on wear volume (V) and the friction coefficient (μ) behavior 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 wear volume and friction coefficient, as described: i) a low value of abrasive slurry concentration generated “grooving abrasion”, which was related to a relatively low wear volume and high friction coefficient; ii) a high value of abrasive slurry concentration generated “rolling abrasion”, which was related to a relatively high wear volume and low friction coefficient.

Keywords: micro-abrasive wear, grooving abrasion, rolling abrasion, thin films, wear volume, friction coefficient.

1. INTRODUCTION

The micro-abrasive wear test by rotating 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.

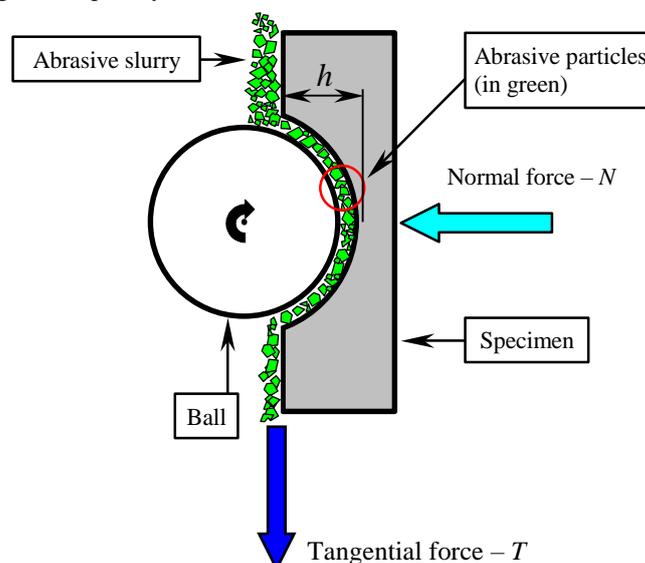


Figure 1. Micro-abrasive wear test by rotating ball: a representative figure showing the operating principle and the abrasive particles between the ball and the specimen; “ h ” is the depth of the wear crater.

Initially, the development of the ball-cratering wear test aimed to measure the thickness of thin films (Rutherford and Hutchings, 1997) (Figures 2a and 2b) using the equations detailed in the article of Cozza (2013). Because of the technical features, this type of micro-abrasive wear test has been applied to study the tribological behavior of different materials (Mergler and Huis in 't Veld, 2003; Cozza *et al.*, 2009; Cozza *et al.*, 2015), for example, in the analysis of the wear volume (V), wear coefficient (k) and friction coefficient (μ) of thin films (Rutherford and Hutchings, 1996; Batista *et al.*, 2002(a); Kusano *et al.*, 2004; Schiffmann *et al.*, 2005; Cozza *et al.*, 2006; Cozza, 2013).

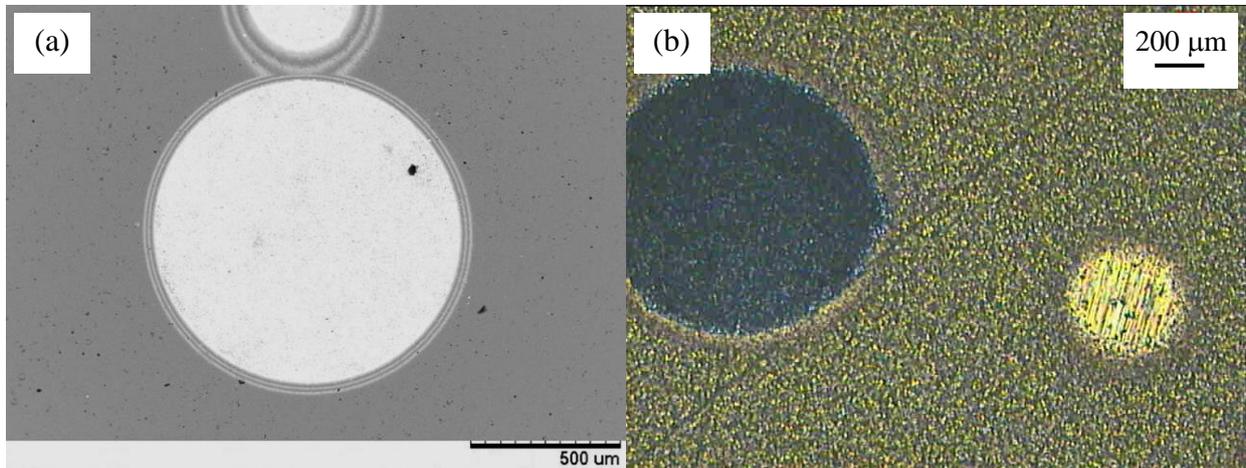


Figure 2. Examples of wear craters generated on coated system: (a) multi-layer and (b) thin film of TiN.

As a function of the abrasive slurry concentration, two micro-abrasive wear modes can usually be 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 and 3b present, respectively, images of “*grooving abrasion*” and “*rolling abrasion*”.

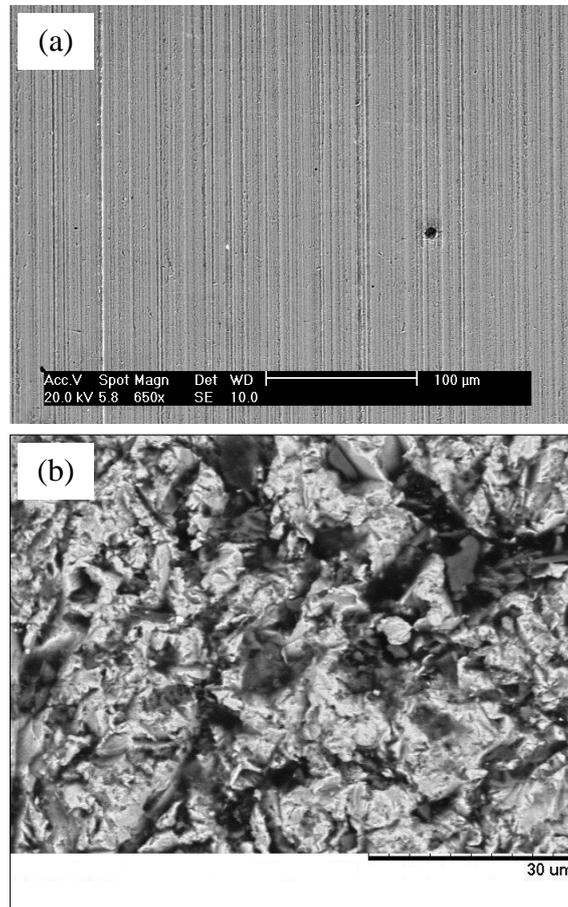


Figure 3. Micro-abrasive wear modes: (a) “*grooving abrasion*” and (b) “*rolling abrasion*”.

When analyzing and studying important research regarding the tribological behavior of materials submitted to micro-abrasive wear tests conditions (Batista *et al.*, 2002(a); Batista *et al.*, 2002(b); Kusano *et al.*, 2004; Schiffmann *et al.*, 2005; Cozza, 2014(a); Cozza, 2014(b); Cozza, 2015), the purpose of this article is to report the influence of the micro-abrasive wear modes on the behavior of the wear volume (V) and friction coefficient (μ) of thin films submitted to micro-abrasive wear tests by rotative ball.

2. EQUIPMENT, MATERIAL AND METHODS

2.1 Ball-cratering wear test equipment

A ball-cratering wear test equipment with “free-ball” mechanical configuration (Figure 4) was used for the micro-abrasive wear tests, which has two load cells: one load cell to control 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.

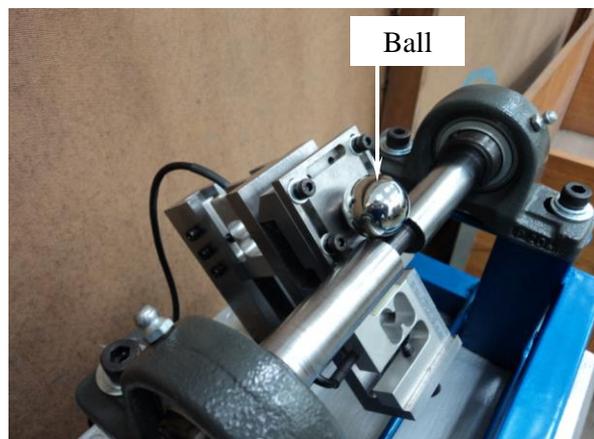


Figure 4. Ball-cratering micro-abrasive wear test equipment used in this work: “free-ball” mechanical configuration, able to simultaneously acquire the “normal force – N ” and the “tangential force – T ”.

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 ($D = 1''$ – standard size) was used.

The abrasive material was black silicon carbide (SiC) with an average particle size of $3 \mu\text{m}$; Figure 5 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.

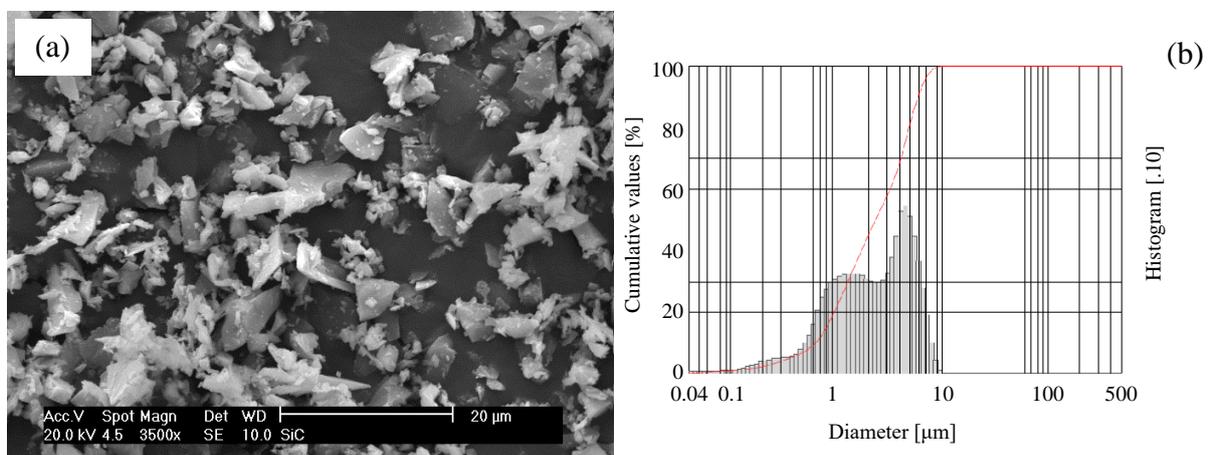


Figure 5. SiC abrasive: (a) scanning electron micrograph and (b) particle size distribution.

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]	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 slurry concentrations (C), $C_1 = 5\%$ SiC + 95% glycerine and $C_2 = 50\%$ SiC + 50% glycerine (volumetric values), with the purpose of respectively producing “*grooving abrasion*” and “*rolling abrasion*” on the surfaces of the thin films. The rotational ball speed was set at $n = 70$ 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 wear volume (V) and the friction coefficient (μ) were then calculated using Equations 1 (Rutherford and Hutchings, 1997) and 2, respectively; “ d ” is the diameter of the wear crater and “ R ” is the radius of the ball.

$$V \approx \frac{\pi d^4}{64R} \quad \text{for } d \ll R \quad (1)$$

$$\mu = \frac{T}{N} \quad (2)$$

3. 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, $h \approx 8 \mu\text{m}$ – the total thickness of the coatings is $t_c \approx 15 \mu\text{m}$. 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.* (1999), 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*”.

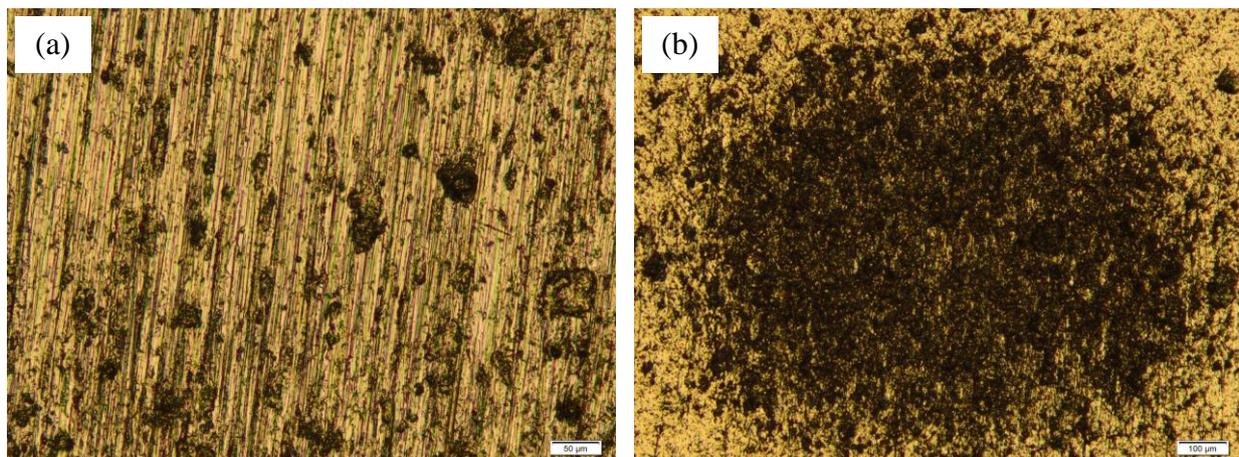


Figure 6. Occurrence of (a) “*grooving abrasion*” and (b) “*rolling abrasion*” on the surface of the thin film of TiN.

The actions of the micro-abrasive wear modes showed an important influence on the wear volume and friction coefficient 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 wear volume and a decrease in the friction coefficient.

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

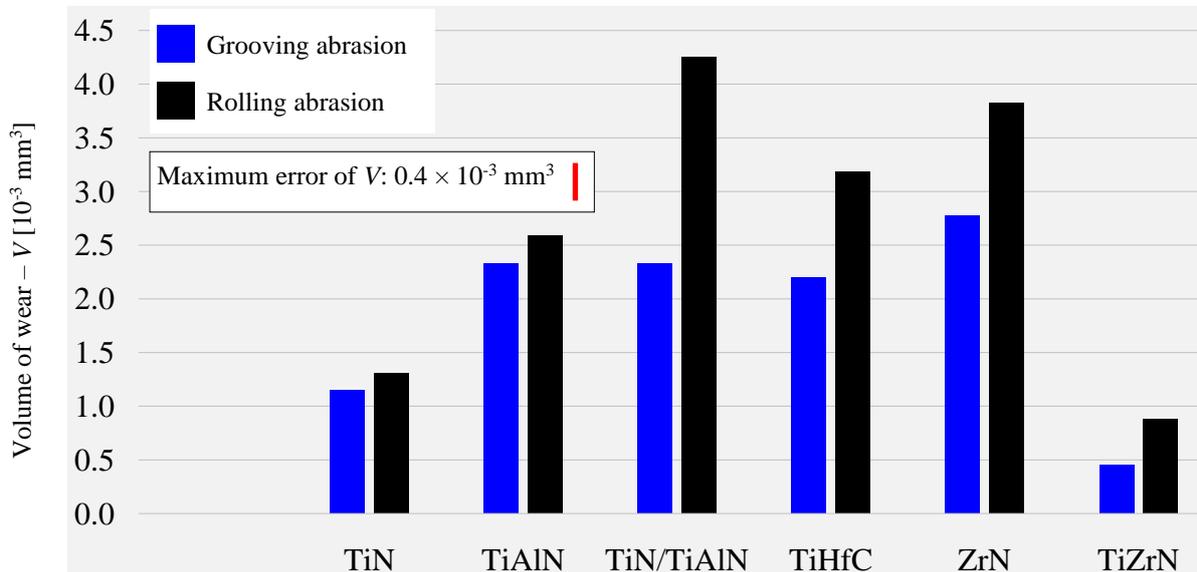


Figure 7. Wear volume of (V) as a function of the micro-abrasive wear modes “*grooving abrasion*” and “*rolling abrasion*”.

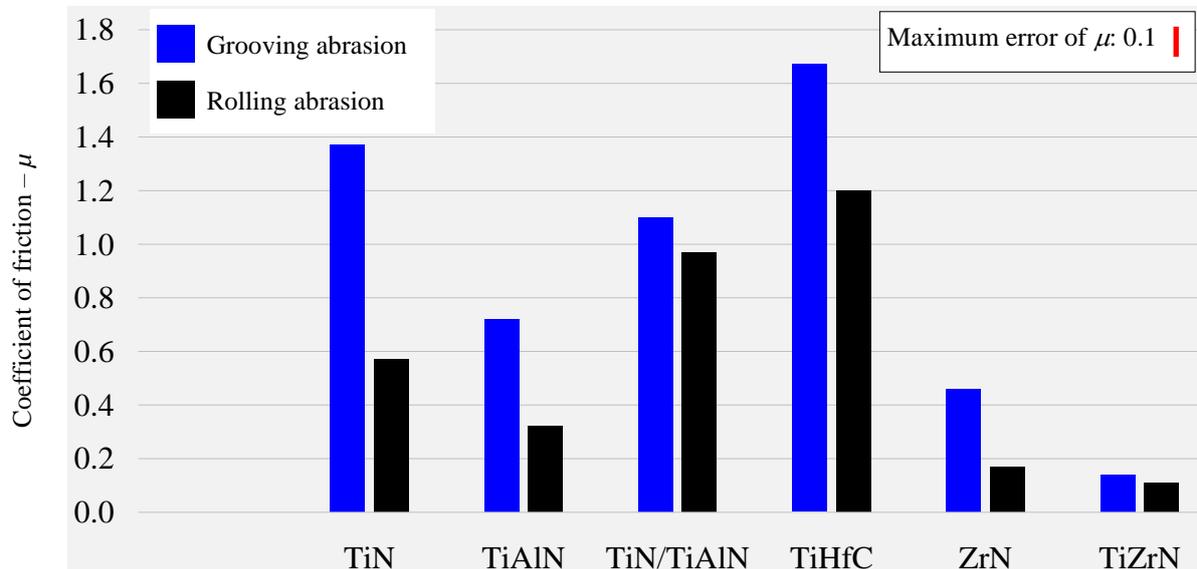


Figure 8. Friction coefficient (μ) as a function of the micro-abrasive wear modes “*grooving abrasion*” and “*rolling abrasion*”.

The values of the wear volume reported under conditions of “*rolling abrasion*” (high abrasive slurry concentration – $C_2 = 50\% \text{ SiC} + 50\% \text{ glycerine}$) were higher than the values of the wear volume reported under conditions of “*grooving abrasion*” (low abrasive slurry concentration – $C_1 = 5\% \text{ SiC} + 95\% \text{ glycerine}$), as reported by Trezona *et al.* (1999) and Mergler and Huis in ‘t Veld (2003). This tribological behavior can be justified because under the occurrence of “*rolling abrasion*”, there is a larger amount of abrasive particles acting between the test sphere and the specimen, participating of the micro-abrasive wear process and, consequently, generating a higher wear volume.

The values of the friction coefficient reported under “*grooving abrasion*” (low abrasive slurry concentration – $C_1 = 5\% \text{ SiC} + 95\% \text{ glycerine}$) were higher than the values of the friction coefficient reported under “*rolling abrasion*” (high abrasive slurry concentration – $C_2 = 50\% \text{ SiC} + 50\% \text{ glycerine}$) 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 friction coefficient 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.

4. CONCLUSIONS

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

- (1) The concentration of abrasive slurry affected the occurrence of “*grooving abrasion*” or “*rolling abrasion*”, as predicted by literature (Trezona *et al.*, 1999);
- (2) With the low concentration of the abrasive slurry ($C_1 = 5\% \text{ SiC} + 95\% \text{ glycerine}$), “*grooving abrasion*” was produced on the surfaces of the thin films;
- (3) With the high concentration of the abrasive slurry ($C_2 = 50\% \text{ SiC} + 50\% \text{ glycerine}$), “*rolling abrasion*” was produced on the surfaces of the thin films;
- (4) The volume of wear increased with the increase of the abrasive slurry concentration (from $C_1 = 5\% \text{ SiC} + 95\% \text{ glycerine}$ to $C_2 = 50\% \text{ SiC} + 50\% \text{ glycerine}$);
- (5) With the low concentration of abrasive slurry ($C_1 = 5\% \text{ SiC} + 95\% \text{ glycerine}$), “*grooving abrasion*” and, consequently, high values for the friction coefficient were reported. In this situation, the abrasive particles were incrustated on the counter-body, hindering their movements and generating high tangential forces;
- (6) On the other hand, when the high concentration of abrasive slurry ($C_2 = 50\% \text{ SiC} + 50\% \text{ glycerine}$) 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 friction coefficient.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

The Authors are the only responsible for the printed material included in this paper.

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	[$\text{mm}^3/\text{N.m}$]
n	Ball rotational speed	[rpm]
N	Normal force	[N]
R	Radius of the ball	[mm]
t_c	Thickness of the thin film	[μm]
T	Tangential force	[N]
V	Volume of wear	[10^{-3} mm^3]

Greek letter

μ Coefficient of friction