Chapter

Thin Films: Study of the 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 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 related to a relatively low volume of wear and high coefficient of friction, and (ii) a high value of abrasive slurry concentration generated "rolling abrasion," which was related 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

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.

Initially, the development of the ball-cratering wear test aimed to measure the thickness of thin films (**Figure 2a** and **b**) [1], which can be made using the equations detailed in Ref. [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.

Figure 3a [11, 12] and **Figure 3b** presents, respectively, images of "grooving abrasion" and "rolling abrasion."

Many works on coefficient of friction (μ) during abrasive wear and other types of tests are available in the literature [13–19], but only a few were dedicated to the coefficient of friction in ball-cratering wear tests [2–4, 10, 11]. In particular, Shipway [20] has studied the coefficient of friction in terms of the shape and movement of the abrasive particles, Kusano and Hutchings [21] presented a theoretical model for coefficient of friction in micro-abrasive wear tests with "free-ball" equipment configuration, and Cozza et al. [2–4, 11, 22] measured the tangential force developed during tests conducted in a "fixed ball" equipment configuration, which allowed direct calculation of the friction coefficient by the ratio between the tangential and normal forces. Besides, using a proper electronic instrumentation, Cozza et al. [2, 23–25] have studied and measured the behavior of the coefficient of friction in thin films in ball-cratering wear tests; however, in those works [2, 23–25], the test sphere has reached the substrate.

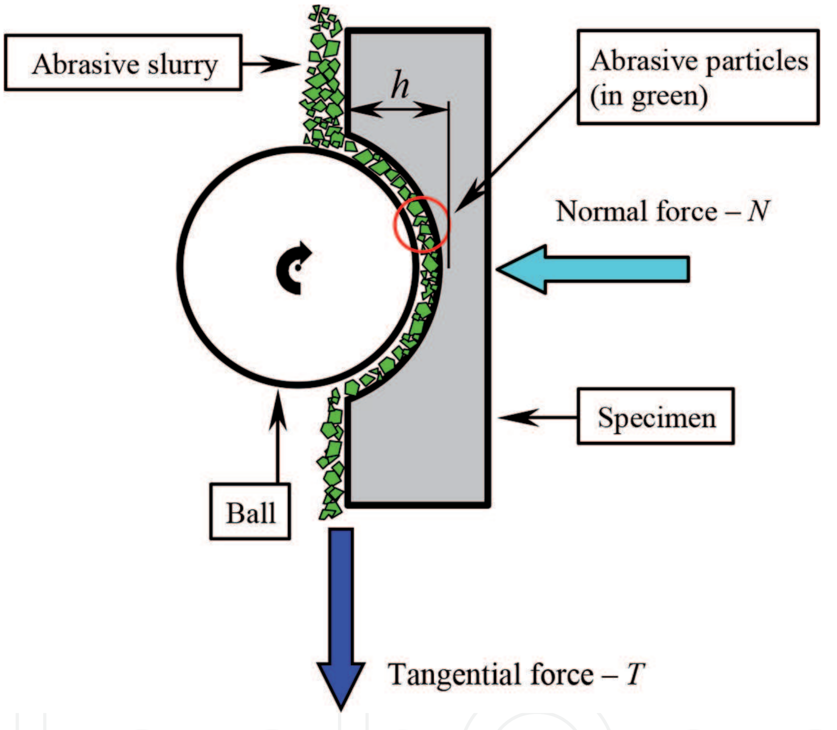

Figure 1.
Micro-abrasive wear test by rotating ball: a representative figure showing the operating principle and the abrasive particles between the ball and the specimen; "h" is the depth of the wear crater.

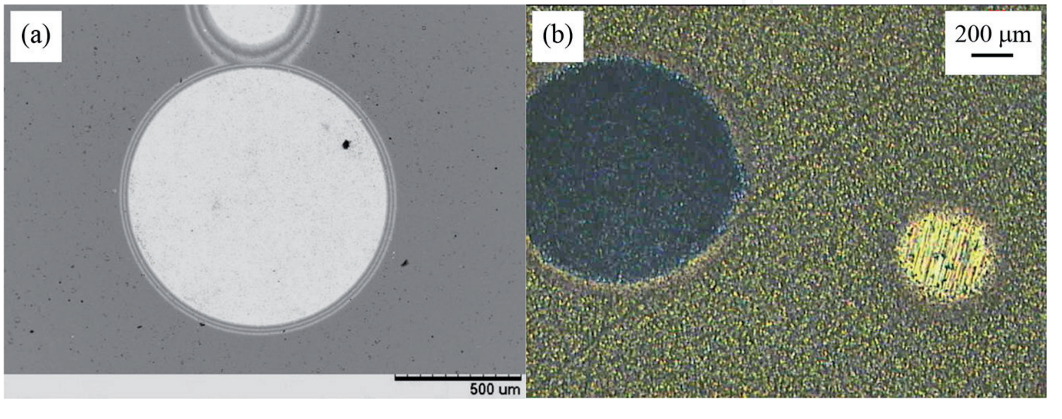

Figure 2.
Examples of wear craters generated on coated system: (a) multilayer and (b) thin film of TiN.

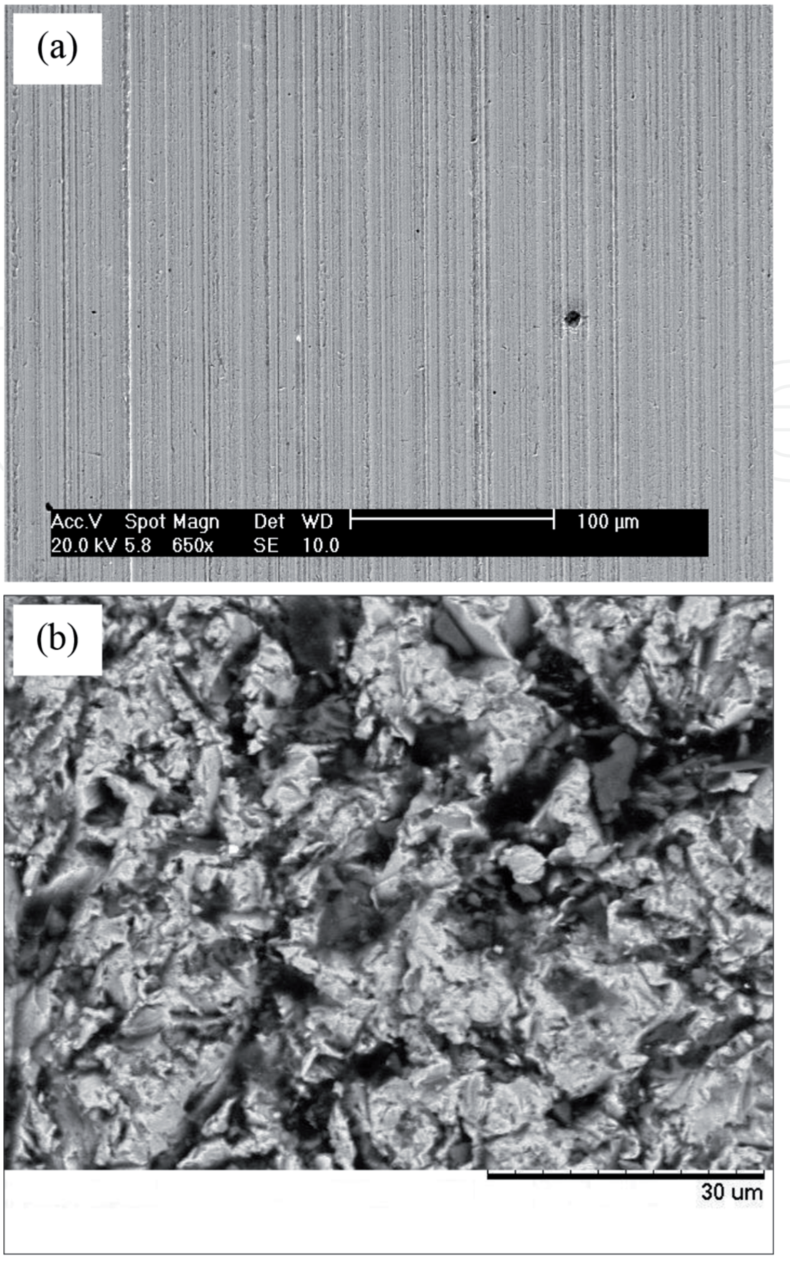

Figure 3.
Micro-abrasive wear modes: (a) "grooving abrasion" [11, 12] and (b) "rolling abrasion."

Analyzing and studying important researches regarding to tribological behavior of materials submitted to micro-abrasive wear test conditions [7–9, 26], 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 rotating 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 4** [27]) 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.

2.2 Materials

Experiments were conducted with thin films of:

- TiN
- TiAlN
- TiN/TiAlN
- TiHfC
- ZrN
- TiZrN

deposited on substrates of cemented carbide. For the counter-body, one ball of AISI 52100 steel with 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 5** [4] presents a micrograph of the abrasive particles (**Figure 5a**)

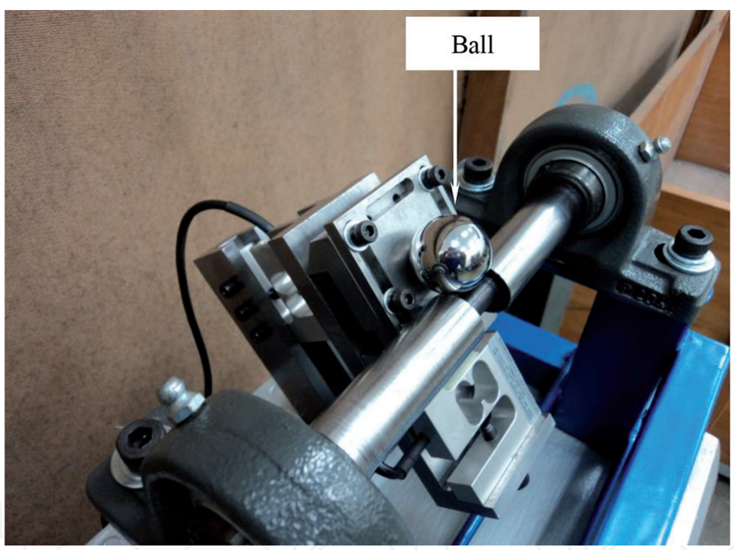

Figure 4.
Ball-cratering micro-abrasive wear test equipment used in this work: free-ball mechanical configuration, able to acquire, simultaneously, the "normal force N*" and the "tangential force* T*."*

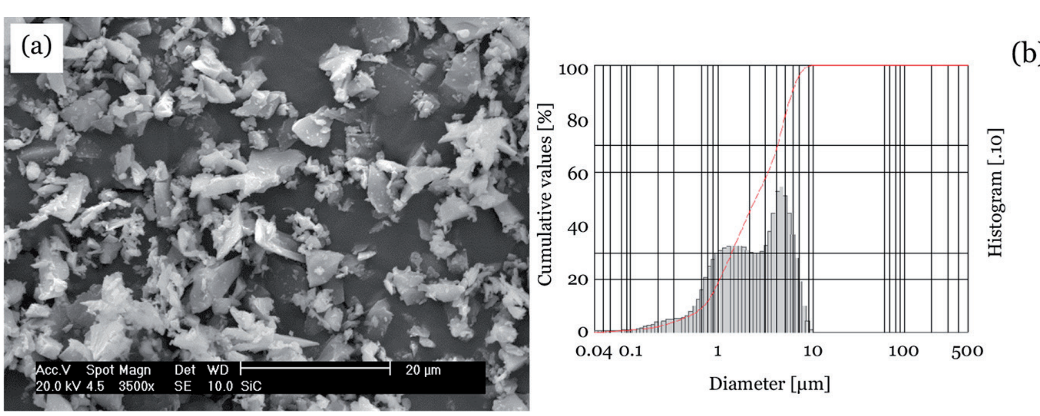

Figure 5.
SiC abrasive [4]: (a) scanning electron micrograph and (b) particle size distribution.

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
Applied on thin films of: **TiN** **TiAlN** **TiN/TiAlN** **TiHfC** **ZrN** **TiZrN**		

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

and the particle size distribution (**Figure 5b**). The abrasive slurries were prepared with SiC and glycerine.

2.3 Methods

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

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 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 Eqs. (1) [1] and (2), respectively; "d" is the diameter of the wear crater, and "R" is the radius of the ball:

$$V \approx \frac{\pi d^4}{64R}, \text{for } d < < R \tag{1}$$

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

3. Results and discussion

Figures 6 and 7 show examples of worn surfaces obtained in the experiments; in all wear craters, the maximum depth (h) observed was, approximately, $h \approx 8$ µm. **Figure 6** displays the action of "grooving abrasion," characteristic of C_1 = 5%

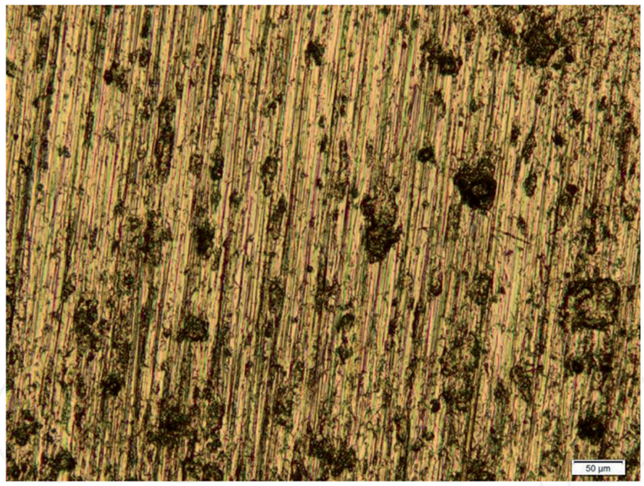

Figure 6.
Occurrence of "grooving abrasion" on the surface of the thin film of TiN.

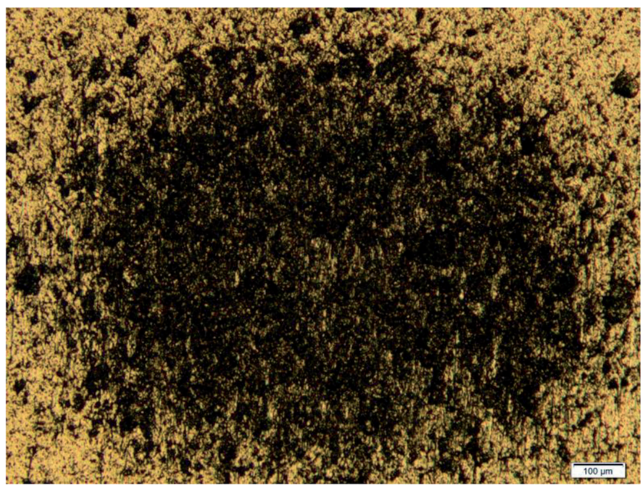

Figure 7.
Occurrence of "rolling abrasion" on the surface of the thin film of TiN.

SiC + 95% glycerine; **Figure 7** 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. [28], 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."

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 8 and **9** 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.

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

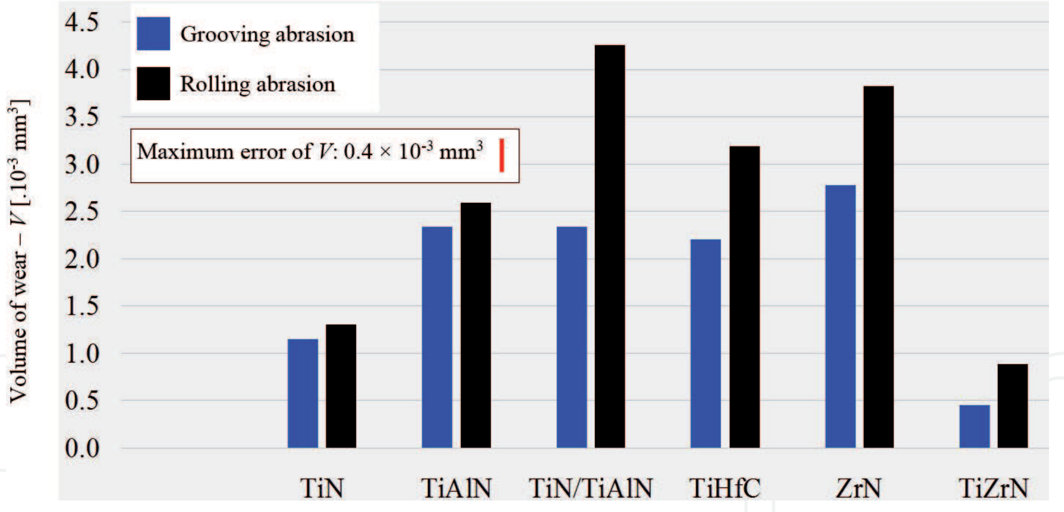

Figure 8.
Volume of wear (V) as a function of the micro-abrasive wear modes' "grooving abrasion" and "rolling abrasion."

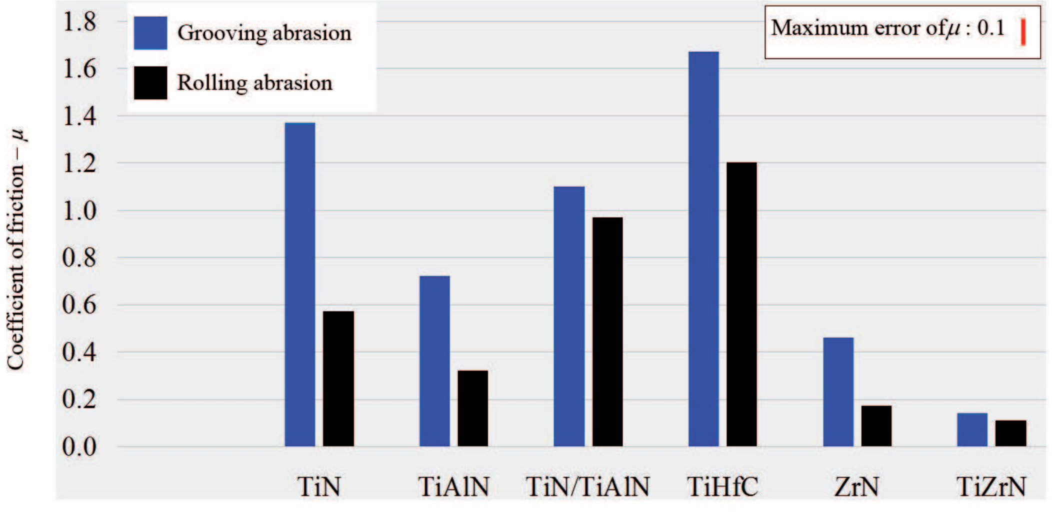

Figure 9.
Coefficient of friction (μ) as a function of the micro-abrasive wear modes' "grooving abrasion" and "rolling abrasion."

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. [28].

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.

4. Conclusions

The results obtained indicated the conclusions:

1. The concentration of abrasive slurry affected the occurrence of "grooving abrasion"—under low concentration—or "rolling abrasion," under high concentration.

2. The volume of wear increased with the increase of the abrasive slurry concentration.

3. With the low concentration of abrasive slurry, "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.

4. On the other hand, when the high concentration of abrasive slurry 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.

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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