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Effect of counterparts on the tribological properties of TiCN coatings with low carbon concentration in water lubrication

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ABSTRACT

TiN and TiCN coatings have long been used for wear reduction in application like tooling, but there are other potential industrial applications in aqueous environments. Therefore, the current investigation explores the friction and wear compatibility of TiN and TiCN coatings against potential sliding partners in water. 316 L discs coated with TiN and TiCN (containing 2.46 at% C) slid against fixed balls of Al_2O_3, SiC, Si_3N_4, and SUS440C in water. In terms of mean steady-state friction coefficient, the ranking from low to high was: SiC < Si_3N_4 < Al_2O_3 < SUS440C regardless of coating type. It is proposed that due to lubrication by silica gel, the friction coefficients and wear rates of TiCN coatings against SiC and Si_3N_4 balls were lower than those against Al_2O_3 and SUS440C balls. For the TiCN/SUS440C tribopairs, tribo-oxidation occurred easily for SUS440C ball, and the oxides on the wear track caused the highest friction coefficient and the roughest wear surfaces. But wear of the TiCN/Al_2O_3 tribopairs, which had the highest wear rate of the coatings, was dominated by abrasion. In terms of the friction and wear behavior under water-lubricated test conditions, SiC was the most suitable counterpart for TiCN-coated stainless steel.

1. Introduction

Due to a satisfactory combination of TiC, TiN and a-C with high hardness, favorable toughness and low friction coefficient [1–4], TiCN coatings have been already paid more attention in modern industry field. Polcar et al. [5] pointed out that TiCN coatings exhibited lower friction coefficient than TiN coatings under different temperatures. On the other hand, at room temperature, nc-TiCN/a-SiCN coatings showed superior tribology to nc-TiN/a-SiN coatings [6], and the similar results have been reported in Refs. [7,8]. It is worth noticing that the friction conditions in all above-mentioned literatures were dry environment. In order to meet the requirements of environment protection and energy saving, TiCN coatings have been expected to be used in water environment. Currently, favorable tribology of TiCN coatings in aqueous environment such as HBSS, seawater and water-based slurry has been covered [9–11]. Regarding the tribology of TiCN coatings in water lubrication, Wang et al. [12] reported that the TiCN/SiC tribopair exhibited low friction coefficient (0.17) and low coatings wear rate (2.3×10^{-6} mm^3/Nm). Nevertheless, the mechanical and tribological properties of TiCN coatings were subject to C concentration [13–16]. Wang et al. [17] pointed out that the TiCN coatings with the C concentration of 2.46 at% exhibited excellent tribological properties as they studied the influence of C concentration on tribological property of TiCN/SiC tribopair in water lubrication. As is known, a tribopair comprised two objects. Apart from coating itself, counterpart is also a non-ignorable factor to tribology. As seen in Table 1 [12,18–22], the friction coefficients and the coatings wear rates were governed by counterparts. Thus, if the TiN(C) coatings are expected to be used in water environment, it was imperative to select the optimal counterpart to the TiCN coatings in water lubrication. However, the research work related to the effect of counterpart on the tribological properties of TiCN coatings in water has not yet been performed.

The aim of this study is to find the optimal counterpart via comparing the friction and wear properties of TiCN coatings (2.46 at% C) sliding against Al_2O_3, SiC, Si_3N_4 and SUS440C balls in water lubrication, and to indicate the wear mechanisms of different tribopairs in water.

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Table 1
Tribological properties of different tribopairs in previous literatures.

References	Coatings	Counterparts	Normal load	Velocity	Model	Environment	Friction coefficient	Wear
Yamane [18]	PTFE	Mild steel Bronze Alumium	10 MPa	0.036 m/s	Pin-on-disk	Dry	0.15 0.15–0.20 0.17–0.5	<120 mg <100 mg <250 mg
Wang [12]	TiCN	SiC SUJ2 SUS440C	3 N	0.100 m/s	Ball-on-disk	Deionized water	0.20 0.30 1.00	3.4×10^{-6} mm^3/Nm 1.0×10^{-6} mm^3/Nm 1.4×10^{-6} mm^3/Nm
Badiskh [19]	TiN	Al_2O_3 Ball-bear steel Mild steel Austenitic steel	2 N	0.100 m/s	Ball-on-disk	Dry 35% humidity	0.17 (25 m running-in) 0.17 (70 m running-in) 0.17 (300 m running-in) 0.90	1.3×10^{-7} mm^3/Nm 2.8×10^{-7} mm^3/Nm 2.1×10^{-7} mm^3/Nm 1.1×10^{-6} mm^3/Nm
Zhou [20]	BCN	Al_2O_3 Si_3N_4 SiC SUS440C	0.2 N	0.200 m/s	Ball-on-disk	Nitrogen	0.60 0.62 0.73 0.89	3.3×10^{-5} mm^3/Nm 5.1×10^{-5} mm^3/Nm 2.2×10^{-5} mm^3/Nm 1.1×10^{-5} mm^3/Nm
Kovalcikova [21]	SiC-HP	ZrO_2 WC–Co Al_2O_3 Si_3N_4	5 N	0.100 m/s	Ball-on-disk	Dry 30% humidity	0.45 0.46 0.50 0.62	1.6×10^{-6} mm^3/Nm 2.2×10^{-6} mm^3/Nm 3.1×10^{-6} mm^3/Nm 2.8×10^{-5} mm^3/Nm
Zhou [22]	a-CN$_x$	Si_3N_4 SiC SUJ2 SUS440C Al_2O_3	5 N	0.160 m/s	Ball-on-disk	Deionized water	0.013 0.017 0.072 0.075 0.100	1.5×10^{-8} mm^3/Nm 4.7×10^{-8} mm^3/Nm 2.3×10^{-8} mm^3/Nm 4.1×10^{-8} mm^3/Nm 1.8×10^{-7} mm^3/Nm

2. Experimental details

2.1. Deposition of TiN and TiCN coatings

After 316 L disks (Ø30 × 4 mm^2) were polished by precision polishing machine (UNIPOL 802) and cleaned ultrasonically in ethanol for 10 min., the steel disk and Si(100) wafer were attached on rotating holder in the chamber of the closed-field unbalanced magnetron sputtering system (UDP-650, Teer Coatings Limited, UK). At first, the substrates were sputter cleaned by Ar$^+$ ion plasma at the bias voltage of -450 V, and then coated with a pure titanium interlayer ($\sim$0.2 μm) in advance. Subsequently, TiN and TiCN coatings were deposited via adjusting the sputtering current of pure titanium (Ti) and graphite (C). The specific deposition parameters are listed in Table 2.

2.2. Characterization of TiN and TiCN coatings

The coatings on Si(100) wafers were used for the characterization of microstructure and mechanical property while the coatings on 316 L discs were used for tribotests. To be specific, Raman spectroscopy (Invia RENSHAW 2000) and X-ray photoelectron spectroscopy (XPS, VG ESCALAB 220i-XL) were adopted to confirm their microstructure and element concentration. Micro-XAM™ white-light profilometer (ADE Phase-Shift, USA), Nano-Indenter XP (Nano Instruments; Inc., Oak Ridge, Tennessee) and Field Emission Scanning Electron Microscope (FE-SEM) (JEOL-JSM-7001F) were used to measure surface roughness, hardness and thickness as well as surface microstructure. The penetration depth of indentation for TiN and TiCN coatings was set as 160 nm and indentation for each sample was repeated 10 times.

2.3. Friction tests of TiN and TiCN coatings

First, according to our previous experience, the Si-based non-oxide ceramics are tribo-hydrated easily in comparison to Al_2O_3 in water, which makes them be suitable in water lubrication. Second, stainless steel is common material in current mechanical industry. Thus, Al_2O_3, SiC, Si_3N_4 and SUS440C balls (Ø8 mm) in Table 3 were chosen as counterparts. The balls roughness was measured by Surfcom-1500DX profilometer and their mechanical properties were obtained from the balls company directly. The tribological properties of coatings sliding against the four kinds of balls in deionized water were investigated using ball-on-disk tribometer (Fig. 1a). By being observed from direction *A*, the section in frame with dash line could be drawn as Fig. 1b. Prior to friction test, the radius (*R*) of wear track could be controlled by moving stage B in horizontal direction. The normal force (2 N) was applied on ball according to lever principle, the rotating speed (0.1 m/s) was controlled by an electric motor, and the total sliding distance was 500 m. Then a round wear track would be formed on the coatings surface. Each test was done for twice or three times to ensure the reliability of data.

Table 2
Deposition parameters of coatings.

Name	Parameter	Thickness
Atmosphere	N_2:Ar (3:10)	–
Chamber pressure	0.227 Pa	–
Temperature	Room temperature	–
Bias voltage	-60 V	–
Rotating speed of holder	10 rpm	–
Current of titanium target	8 A	–
Current of graphite target	0 A (TiN)	1.14 μm
	3 A (TiCN)	1.24 μm

Table 3
Mechanical properties of Al_2O_3, SiC, Si_3N_4 and SUS440C balls.

Counterpart balls	[a]Hardness *H* (GPa)	[a]Elastic modulus *E* (GPa)	Roughness *Ra* (nm)	[a]Poisson ratio *ν*
Al_2O_3	16.5	370	52.8	0.24
SiC	22	430	88.5	0.14
Si_3N_4	15.3	308	55.2	0.27
SUS440C	7.2	204	53.3	0.28

[a] The data were from the balls company.