Available online at www.sciencedirect.com

SCIENCE DIRECT®

Surface & Coatings Technology 195 (2005) 234–244

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

Friction and wear characteristics of a Ti-containing diamond-like carbon coating with an SRV tester at high contact load and elevated temperature

J.H. Ouyang, S. Sasaki*

Tribology Group, National Institute of Advanced Industrial Science and Technology (AIST), 1-2 Namiki, Tsukuba, Ibaraki 305-8564, Japan

Received 9 February 2004; accepted in revised form 25 June 2004
Available online 21 August 2004

Abstract

The friction and wear characteristics of a Ti-containing diamond-like carbon (Ti-DLC) coating have been evaluated with a Schwingungs Reibung und Verschleiss (SRV) tester when reciprocating sliding against a steel ball and a CrN-coated pin at high contact load and elevated temperature under a boundary-lubricated condition. The Ti-DLC coatings exhibit a friction coefficient of 0.06–0.12 and a wear rate of 1.99×10^{-10} to 9.5×10^{-7} mm^3/N m, depending on the counterfaces, load and temperature. The Ti-DLC/CrN-coated pin pair shows a low friction coefficient than the Ti-DLC/steel ball pair under the identical wear conditions. Increasing the test temperature reduces the coefficient of friction and, however, clearly increases the wear rate of the Ti-DLC coatings at 20 N. At 50 N and 150 °C, the Ti-DLC coating was removed completely and the wear was applied to the substrate. At below 100 °C, the wear mechanism of the Ti-DLC coatings is dominated by surface polishing effects. At 150 °C, brittle fracture, delamination, partial graphitization, and tribo-chemical reactions are found in the tribo-contact areas. The formation of iron oxides on worn surfaces of the Ti-DLC coatings at 150 °C is attributed to the dissolved oxygen in the oil lubricant and the tribo-chemical reactions. Furthermore, these friction and wear data have been compared quantitatively with pure DLC coatings and multilayered VTiN coatings under the identical wear conditions.

Keywords: Ti-DLC coating; Friction; Wear; Elevated temperature; Tribo-chemical reactions

1. Introduction

Carbon-based coatings, such as diamond and diamond-like carbon (DLC), have the increasing market potential due to their high hardness, excellent mechanical and tribological properties [1–10]. With the advent of new mass-production technologies in the family of physical vapor deposition (PVD) and chemical vapor deposition (CVD), diamond and diamond-like films, and coated products have reached a greater level of activity in their industrial applications [1–13]. Table 1 gives the influences of production technology on properties of carbon-based coatings available in the market. The DLC-based coating can be produced at substrate temperature below 200 °C, which is a major advantage over the high temperature production technology required for the growth of micro- or polycrystalline diamond coatings [3,4,9,10]. Different properties in residual compressive stress conditions, hardness, atomic density, deposition energy, hydrogen content and bonding types of carbon atoms will be produced in diamond and diamond-like carbon coatings, strongly depending on the production technologies [3,9,10]. Hard DLC coatings, consisting of a high cross-linked network of carbon atoms, have high compressive stress. In many cases, such DLC coatings are characterized by a high sp^3/sp^2 ratio of C–C bonding in their structure. However, the high stress values often lead to poor adhesion with the substrate, especially on steel and, therefore, limit its use in practical applications [10]. Balinit® DLC developed by Balzers, for machining aluminum alloys and other nonferrous metals, has hardness rating of over 2500 $HV_{0.05}$, low friction coefficient of 0.1–0.2 in unlubricated test against steel, and the adhesion-reducing ability up to 350 °C at cutting edge. Physical vapor

* Corresponding author. Tel.: +81 29 8617196 fax: +81 29 8617844.
E-mail address: shinya-sasaka@aist.go.jp (S. Sasaki).

0257-8972/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.surfcoat.2004.06.041

Table 1
The influences of production technology on properties of carbon-based coatings in the market

Coatings	Me-a-C:H	Soft DLC	ADLC, a-C:H	Hard DLC, a-C or ta-C	Microcrystalline diamond	Polycrystalline diamond
Production technique	MSIP, MeC target, Bias voltage,	MSIP, C target, Bias voltage, MF	PA-CVD, DC-RF, CH_4, C_2H_2	arc PVD, C target, no reactive gas	CVD (hot filament, HCDCA)	free standing CVD, high-pressure synthesis, coating brazed/ sintered on tool
Deposition temperature	~200 °C	<200 °C	<200 °C	<200 °C	>800 °C	
Hardness (GPa)	1000–2000	1000–4000	2000–4000	6000–8000	>8000	
Friction coefficient (μ)	0.1–0.2	0.05–0.2	0.1–0.2	0.1–0.2		
Typical thickness range	1–4 μm	1–5 μm mainly sp^2 bondings	2–3 μm	1–2 μm sp^3 bonding share: >70%	5–9 μm only sp^3 bondings	40 μm–3 mm
Offered by	Balzers (Balinit® C)	Bernex (blackbond, Ti-a-C-H)	Balzers (Balinit® DLC)	Bernex (Tetrabond, a-C)	Balzers (Balinit® Diamond)	De Beers
	Metaplas (Maxit® W-C:H)	Eifeler (Graphit-iC™)	Bernex (ADLC, a-C:H)	Eifeler (Diamanta)	Cemecon (CCDia® 08)	GE
	Morgan (Diamonex® DLC)	Teer coatings (Graphit-iC™)	Bekaert (DLC, a-C:H)	Diarc	OSG	Sumitomo
	Sumitomo	CemeCon (DLC 3000)	Mitsubishi Sumitomo			Morgan (Diamonex CVD diamond)

Magnetron sputter ion plating (MSIP), plasma-assisted CVD (PA-CVD), amorphous DLC (ADLC), DC/medium/radio frequency (DC/MF/RF), tetrahedral a-C (ta-C).

deposited DLC coating showed the lowest coefficient of friction when running against cast iron cylinder segments in a blend of engine oil and E85 fuel for piston ring applications as contrasted to thermal sprayed molybdenum, and CrN coatings [6].

The amorphous nature of DLC opens the possibility to introduce certain amounts of additional elements, such as Si, F, N, O, W, Nb, Cr, V, Co, Mo, Ti and their combinations, into the film and still maintain the amorphous phase of the coating [1–4,7,9,10]. By this technique, different film properties such as tribological properties, electrical conductivity, surface energy and biological reactions of cells in contact with the surface can be continuously adapted to a desired value [1,9,12,13]. The influence of various additional elements in DLC coating has been widely investigated [1,2,7,9,10]. The additions of N, F, B, O and Si has been proposed to improve the internal stress, surface tension, surface energy, wetting behavior, optical transparency, scratch resistance and UV protection, while the additions of W, Ag and Cu metals are able to improve the electrical conductivity, biological reactivity and other decorative effects [1–3,10,12]. The addition of Si was reported to offer a viable route for making DLC-based coatings suitable for lubricating applications over a wide range of operating humidities [1,2]. The Nb-DLC coatings offer a low friction coefficient and a high performance under adhesive wear loading [10]. The incorporation of F or Si in DLC increased the contact angle of water, while O and N incorporation decreased the contact angle [13]. With the addition of various elements in DLC films to form nano-composite coatings, multilayered DLC films and functionally gradient DLC coatings, it is possible to obtain much lower friction [8]. Balinit® C coatings have been developed for precision components of vehicles and machines [3,10]. They exhibit excellent running-in behaviour, offer good protection in dry or emergency running conditions, and have an oxidation onset temperature up to 300 °C. In order to improve the fuel economy of automotive engines, extensive studies have been done on the reduction of friction loss, especially the wear between cam and follower [5]. Metal-containing DLC coatings were introduced to automotive parts such as plunger, roller pin in fuel injection pump, gear and valve train, which serve at high applied loads and high speeds [5,6]. The friction coefficient of Ti-containing DLC coating was substantially lower than that of pure DLC coating in oil lubricant tested with a pair of cam and follower in a direct acting valve train of the internal-combustion engine [5].

Precision components exposed to very severe tribological conditions often have to meet critical requirements on surface quality. These include enhanced surface hardness, low friction coefficients under high sliding loads, thermal stability and long service life under extreme conditions [3,5,6,9,10]. The degradation temperature of DLC-based coatings depends upon both the deposition method and the specific deposition conditions [14]. It was reported that the tribological behavior of DLC coatings started to change around 100 °C due to thermomechanical effects [14]. At elevated temperatures, most DLC coatings undergo permanent chemical and