Surface & Coatings Technology 222 (2013) 48–54

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Design of low-friction PVD coating systems with enhanced running-in performance — carbon overcoats on TaC/aC coatings

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ARTICLE INFO

Article history:
Received 26 September 2012
Accepted in revised form 1 February 2013
Available online 15 February 2013

Keywords:
Low friction coatings
Surface roughness
Running-in
PVD DLC

ABSTRACT

The widespread use of low friction PVD coatings on machine elements is limited by the high costs associated with fulfilling the demands on the surface quality of both the supporting substrate and the counter surface. In this work, an attempt is made at lowering these demands, by adding a sacrificial carbon overcoat to a TaC/aC low friction coating. Both coatings were deposited by planar magnetron DC sputtering, as separate steps in a single PVD-process. Coatings were deposited on substrates of two different surface roughnesses, in order to test the ability of this coating system to function on rougher substrates. Reciprocating ball on disc tests was performed, using balls with two different surface roughnesses. The worn surfaces were investigated using 3-D profilometry and SEM. The ability of the different overcoats to initially reduce the roughness of both the coated surface and the counter surface and to produce stable, low-friction conditions was examined for the different initial roughnesses. The implications for design of efficient run-in coatings for various systems are discussed.

1. Introduction

Carbon based PVD coatings containing nanocrystalline metal carbides (often described as doped DLC coatings) are well-known for their good tribological properties in many applications [1], and are frequently applied to different machine elements, in order to reduce friction and increase wear life. Due to the high costs related to such coatings, their widespread use is however limited. A considerable part of these costs is related to the preparation of the surfaces on which the coatings are deposited, rather than to the coating deposition process itself. If the demands on surface finish could be reduced, low friction coatings would become a viable option for a much larger range of components.

Asperities on the substrate surface are typically inherited by the coating, and cause concentration of contact stresses during use, leading to an increased risk of coating failure, as well as to abrasive wear of the counter surface. If the coating allows for a gentle running-in wear of both the coating and the counter surface during early stages of use, where the most protruding asperities are worn down, it is however possible to achieve good adhesion and low wear, even on rough substrates [2].

Addition of a softer coating on top of the coating could potentially be used to make sure that such a gentle run-in behaviour is possible. Firstly, a softer overcoat would spread the loads at the asperity level, thus reducing the contact stresses [3,4] and thereby the risk of coating spallation. Secondly, the overcoat could act as a sacrificial layer, where a larger amount of wear would be acceptable during the run-in period. A softer and more ductile coating would be less prone to flaking, and thus able to withstand larger deformations, possibly allowing redistribution of coating material into voids in the surfaces of both the coated surface and the uncoated counter surface.

The initial stage of run-in of this type of coatings typically involves formation of a relatively coarse grained tribofilm on both contacting surfaces [5]. For rougher surfaces, the amount of material transferred during this stage is expected to increase. If the softer overcoat is active during this stage, the wear of the underlying coating is expected to decrease.

In this study, this type of coating system has been tested. As a model system, overcoats of pure carbon of varying thickness were added on top of a previously known low-friction coating, TaC/aC [6].

The topography of carbon based PVD coatings has been studied in several previous studies. The influence of deposition parameters on intrinsic coating topography, and the influence of this topography on the tribological properties have both been investigated [7,8]. It is important to point out that the roughnesses studied in this work are several orders of magnitude larger than typical intrinsic coating topographies, and that no direct comparison with these studies can be made.

2. Experimental

2.1. Coating substrates

Powder metallurgical high speed steel discs (ASP 2030, hardness 9.5 GPa) were used as substrates. Substrates with two different surface

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0257-8972/$ – see front matter
http://dx.doi.org/10.1016/j.surfcoat.2013.02.003

finishes were prepared, hereafter referred to as *smooth* and *rough*. The two types of substrates will be identified by illustrations showing a flat or a pointed disc, respectively, in some of the figures. The smooth substrates were polished to a mirror finish (R_a<10 nm), whereas the rough substrates were ground against SiC abrasive paper (#120 grit), resulting in an R_a of approximately 0.3 μm. All coatings were also deposited on silicon wafers, used for coating characterisation.

Prior to coating, the substrates were ultrasonically cleaned first in acetone (2∗15 min), then alkaline detergent (2∗15 min) and finally ethanol (15 min).

2.2. Coating deposition

The deposition was performed in a commercial PVD-coating system (Balzers, BAI640R), equipped with two planar magnetron sputtering sources and a thermionic arc, used for auxiliary ionisation of the chamber.

Prior to coating deposition, the substrates were pre-heated to approximately 450 °C for 45 min, after which they were argon etched for 15 min at a substrate bias of −200 V and a pressure of 0.15 Pa.

The TaC/aC coating was deposited using planar magnetron DC co-sputtering from a carbon target partially covered by tantalum foil, a procedure described elsewhere [9]. The deposition was performed for 120 min at a total chamber pressure of 0.4 Pa (achieved by an Ar flow rate of 150 sccm), a magnetron power of 1 kW and a thermionic arc current of 100 A. The substrate bias was set to 0 V (floating potential).

A pure carbon overcoat was deposited on top of the TaC/aC coating (without breaking the vacuum) by planar magnetron DC sputtering from a pure carbon target. The power on the magnetron was 500 W. All other process parameters were identical to those used for the TaC/aC deposition. The duration of the deposition was varied, with the purpose of producing carbon layers of 10, 100 and 1000 nm thickness. In order to achieve this, deposition times of 11, 109 and 1090 min were used, calculated from preliminary experiments.

2.3. Coating characterisation

Coating cross sections were studied using HR-SEM (ZEISS 1550), in order to determine their thickness and morphology. Compositional characterisation was performed using SEM/EDS (EDAX LEO 440) at an accelerating voltage of 10 kV. Due to the peak overlap of the TaM and the SiK peaks in the EDS spectra, the analysis was performed on a coating on a smooth steel substrate. Some signal from the underlying substrate was detected; the presented results are normalized values for coating elements and expected contaminants.

The hardness of the two coating layers was determined by nanoindentation (MTS Nano Indenter XP). The indents were performed using a Berkovich diamond indenter, and evaluated using the Oliver–Pharr method [10]. To avoid influence from the underlying material, the indents were made to a maximum depth of 30 nm (less than 10% of the coating thickness). Measurements were performed on the coating without carbon overcoat and on that with the thickest carbon overcoat, both deposited on smooth steel substrates. The latter measurement is considered to represent the hardness of the carbon overcoat.

The topography of unworn coatings, without carbon overcoat and with the thickest carbon overcoat, was also studied by atomic force microscopy (AFM), using a PSI AXE-50 instrument, operated in non-contact mode. The measurements were performed on coatings deposited on silicon substrates, in order to retrieve information about the intrinsic coating topography.

2.4. Counter surfaces

Ball bearing steel balls (ø6 mm, 100Cr6 steel, hardness 9 GPa) were used as counter surfaces in the tribological tests. The balls were used both as purchased (polished to R_a 0.075 μm) and after intentional roughening. This was performed by placing 60 polished balls on a

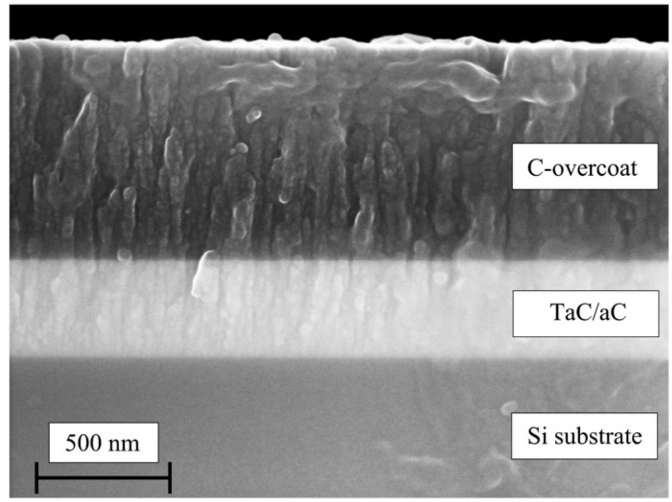

Fig. 1. Fracture cross section of the coating with the thickest carbon overcoat (800 nm), deposited on silicon, imaged by HR-SEM. The two layers of the coating are clearly distinguishable.

#120 grit SiC abrasive paper and loading the balls with a 4 kg circular steel plate which was then rotated 1800 revolutions, causing the balls to roll over the abrasive paper. After this treatment, the balls had an R_a of approximately 0.58 μm. The two types of balls will hereafter be referred to as *smooth* and *rough*. In some of the figures, the type of ball used is indicated by an illustration showing a smooth or pointed ball, respectively.

2.5. Tribological testing

The coatings and counter surfaces were tested in unlubricated reciprocating ball-on-disc sliding in ambient air, under a normal load of 5 N. The stroke of the reciprocating motion was 10 mm and the oscillation frequency 5 Hz (corresponding to an average sliding speed of 0.1 m/s). The test duration was 10,000 sliding cycles, but some tests were stopped earlier, after showing clear signs of coating failure.

The topography of the wear marks on both ball and coating was studied using white light interference profilometry (WYKO NT 1100). The

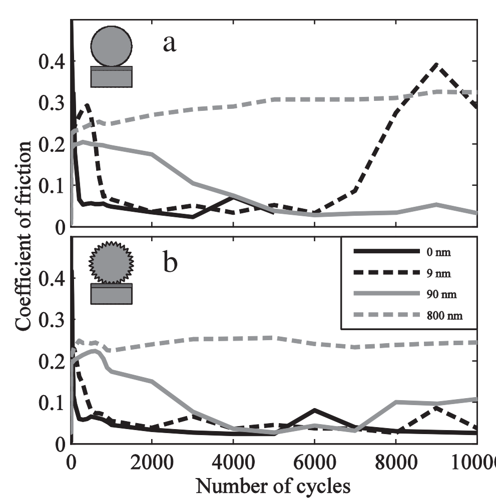

Fig. 2. Coefficient of friction as a function of the number of sliding cycles for the coatings deposited on smooth substrates, running against smooth (a) and rough (b) balls.