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Tribology International 39 (2006) 945–952
TRIBOLOGY INTERNATIONAL
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Topography-related effects on the lubrication of nanostructured hard surfaces

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Received 22 April 2005; received in revised form 27 September 2005; accepted 29 September 2005
Available online 14 November 2005

Abstract

This study reports the effect of nanoscaled surface structure of some hard coatings on the (micro-) frictional behaviour of systems under minimum lubrication conditions with modest contact pressures and low sliding speeds (below 1 mm/s). For this purpose, Cr-N coatings with a randomly crater-like topography and with varying dimensions of surface features as well as a smooth Cr-N surface were tested with a microtribometer. The friction on the samples was measured as a function of the viscosity of the applied mineral base oil and the sliding velocity. For all tests, the structured surfaces exhibited lower friction than the smooth surface. Furthermore, it was possible to detect variations in the lubrication-promoting effect of the structures depending on the oil viscosity and the sliding speed. Indications for the existence of an optimum topographic scale for this type of surface structure were found.

Keywords: Microfriction; Lubricated contacts; Surface topography

1. Introduction

In a lubricated system, friction will vary according to the amount of lubricant present in the contact zone between two surfaces sliding against each other. Under conditions of minimum (or starved) lubrication the lubricant film may no longer be continuous. In this case, lubrication of the contact depends, to a large extent, on retention of the lubricant in cavities present on the surface. Size, geometry and distribution of these cavities are crucial factors that determine the capability of the surface to entrap microscopic quantities of lubricant and to dispense and transport it to the actual contact points within the contact zone. Optimum system performance requires a thorough knowledge of the relationship existing between lubricant properties (e.g. polarity, viscosity), operating conditions (e.g. contact pressure, sliding velocity) and surface properties (e.g. lubricant wettability, topography); the surface topography needs to be adapted accordingly on the basis of this knowledge [1–3]. In recent years, this relationship has been intensively investigated for regular micro-pore arrangements produced by techniques such as vibrorolling [4], reactive ion etching [4], abrasive jet machining [4], lithography and anisotropic etching [4] or laser texturing [2,5–7]. The lateral dimensions of the topography produced by these processes tends to be from tens to hundreds of micrometers, with roughness S_q (or R_a) of 1 μm or more. However, studies of the effect of surface cavities in the sub-micrometer range upon the tribological behaviour are still in their infancy.

In the work reported here the influence of open nanoscale surface cavities on the friction and wear behaviour under minimum (starved) lubrication conditions was investigated for hard Cr-N thin films possessing a random, crater-like topography. The term crater-like refers to a random surface structure topographically similar to that obtained by bombarding a surface from above with particles or brief energy bursts. The surface morphology of the Cr-N films was modified by controlling of the parameters in the plasma-assisted physical vapour

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doi:10.1016/j.triboint.2005.09.005

deposition (PVD) process (in-process structuring). Using in-process structuring, a variety of surface morphologies can be obtained [8], e.g. morphologies with pyramidal or hemispherical features. For this study, the crater-like morphology was chosen because the topographical structure (few asperities above the mean plane, large number of surface cavities) appeared to be interesting for applications requiring a certain lubricant storage capability in the surface.

2. Experimental work

2.1. Sample preparation and characterization

Five chromium nitride (Cr-N) coatings with different structures coated on Si(1 0 0) wafers were investigated. All samples were prepared by unbalanced magnetron (UBM) sputtering in a PVD process. The different surface structures were obtained by adjusting the parameters of the PVD process in a controlled manner (in-process structuring). The critical deposition parameters are given in Table 1.

The reference sample used to compare the performance of the structured Cr-N coatings has a relatively smooth surface characterised by small hillock-like surface features. The other four tested surfaces, labelled C1–C4, exhibit a crater-like morphology with varying crater dimensions. The surface topographies were analysed by atomic force microscopy (AFM) of ten scan areas (scan size: $10\,\mu m \times 10\,\mu m$) measured at randomly located regions on the sample surface. The surface topography was quantitatively analysed by determining various parameters: rms roughness (S_q), ten-point height (R_z), kurtosis (S_{ku}), skewness (S_{sk}), dominant wavelength λ determined in power spectral density (PSD) analysis of the surface, summit density (S_{ds}), summit curvature (S_{sc}) summit slope (S_{ss}) and the void volume at the surface heights at 5% bearing area ($V_{(h0.05)}$). Detailed information concerning these parameters, including their method of determination, can be found in Refs. [9–11]. Since many of the above-mentioned surface parameters depend on the sampling interval of the measuring device [12–14], the fractal dimension D was also determined for the tested surfaces according to the approach described in [15]. In this study, auto-leveling using a least-squares plane was applied before calculating the surface parameters from AFM scans (by using the software Nanoscope III version 5.12r3 by Digital Instruments). In all scans there were 256 sampling points in both x and y directions (sampling interval about 40 nm). Fig. 1 shows examples of the AFM-determined surface topography of the samples. Table 2 gives the values of surface parameters for the different structures shown in Fig. 1.

The hardness of the Cr-N samples, measured by depth-sensing nanoindentation, is included in Table 2.

X-ray diffraction (XRD) analysis revealed that all coatings are single-phase Cr_2N.

2.2. Microtribological tests

Comparative microfriction studies were performed by using a precision microtribometer. This microtribometer (Fig. 2) consists of three basic units: precision motion mechanisms, force transducer and fibre-optic length detection system [16]. The precision motion mechanisms consist of various drives for sample positioning, providing reciprocating motion and for normal force adjustment. The sample positioning drives are stepper motors, while the reciprocating unit consists of a piezo element coupled to a linear guide. Coarse normal force adjustment is achieved by using a stepper motor, while fine adjustment is accomplished with a piezo element. The force transducer is a double leaf spring made from photo-structured glass. By knowing the lateral and the normal force constants of the spring, measured lateral and normal deflections can be transformed to their respective force values. The deflections of the spring, the back and forth motion of the reciprocating unit as well as the vertical motion of the normal force adjustment unit are all measured using fibre-optic sensors based on the principle of reflection intensity variation. More details about design and principle of measurement of this test device are described elsewhere [17].

In this work, microtribological tests consisted of measuring the friction force as a function of the applied normal load at various sliding velocities and lubricated by oils with different viscosities:

- Normal load: 1, 3, 6, 9, 12, 18, 21 mN.
  The tests were carried out under essentially wear-free conditions. Wear mapping tests indicate that the onset of observable wear (plastic deformation of asperities and shearing of deformed material) of this type of coating structures was above 100 mN.

Table 1
PVD parameters adjusted in a reactive UBM sputtering process for deposit the different tested samples on Si(1 0 0)

Sample	Temperature (°C)	Total pressure (Pa)	Ar/N_2 gas flow ratio (-)	Bias voltage (V)	Sputter power (kW)
Reference	350	0.4	1.3	−75	10
C1	450	1.0	0.7	−225	2
C2	350	0.4	1.3	−225	4
C3	250	1.0	1.5	−225	2
C4	350	0.4	1.0	−225	4