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Surface & Coatings Technology 191 (2005) 357–366

SURFACE & COATINGS TECHNOLOGY

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Influence of EP additive concentration on the tribological behaviour of DLC-coated steel surfaces

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Received 8 December 2003; accepted in revised form 2 April 2004
Available online 14 May 2004

Abstract

The influence of the concentration of a conventional extreme-pressure (EP) additive on the wear and friction behaviour of DLC-coated steel surfaces was investigated. Special emphasis was put on exploring a DLC/steel combination operating under boundary lubricated conditions and on determination of how the DLC against steel situation differs from conventional steel against steel contacts in boundary lubricated sliding. Tests were performed in a load-scanning reciprocating test rig, which allowed a wide spectrum of loads to be tested in a single test. The sliding speed was set to 0.1 m/s and the contact pressure was in the range from 2.4 to 5.6 GPa.

This investigation indicated that the life of boundary lubricated DLC-coated surfaces involves several stages. After running-in, the DLC coating, although unable to form a tribofilm on top of the coating, takes an active part in forming a low friction tribofilm on the uncoated steel counterpart or on the exposed steel substrate, which eventually leads to the final wear out of the coating. Further, the concentration of additive has a significant influence on the tribological behaviour of DLC-coated steel surfaces. Contrary to the common rule for steel/steel contacts, reduction of the EP additive concentration may lead to improved tribological behaviour of DLC-coated surfaces.

Keywords: Boundary lubrication; DLC coatings; Extreme-pressure additives; Friction

1. Introduction

Owing to their attractive properties, diamond-like carbon (DLC) coatings are becoming increasingly important in the field of machine components [1–4]. The extreme hardness, high elastic modulus, excellent wear and corrosion resistance, high thermal and chemical stability, and the low frictional nature of these coatings make them good choices for a wide range of tribological applications [2,5–8].

Many types of thin DLC coatings have turned out to provide excellent low friction and wear protection properties under dry sliding conditions. Their friction coefficient against different metallic or ceramic counterparts is typically reported in the range of 0.1 to 0.01 [10–12]. This is in the same range as or lower than typical values for metals in boundary lubricated sliding conditions. Despite this favourable friction level, only few DLC-coated tribological components are likely to be operated without a lubricant. There are many reasons for this. Firstly, tribological properties of unlubricated DLC coatings are sensitive to the surrounding atmospheric conditions, notably the relative humidity [2,13,14]. Further, the lubricant also serves other functions, such as cooling, in mechanical systems. Thus, the majority of DLC-coated mechanical components will continue to be operated under lubricated conditions, and will initially probably use the same oils as originally developed for steel/steel contact.

Under boundary lubrication conditions, tribofilms forming on highly loaded spots may protect metal surfaces from wear. Such protective films are typically generated by tribologically activated reactions between lubricant additives and the metallic surface [15]. Such additives were originally developed to work with the uncoated surfaces of metal parts, i.e. typically iron oxides [22]. Now, with the introduction of wear resistant low friction coatings, such as the extensive family of DLC coatings, the surface chemistry has radically altered, and the whole complicated area of their tribological film formation is still largely unexplored [16,17].

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doi:10.1016/j.surfcoat.2004.04.001

However, previous investigations [18,19] have shown that also in the case of DLC-coated surfaces addition of commercial AW or EP additives to poly-alpha-olefin (PAO) oil may significantly improve the tribological performance. A new type of tribofilm, composed of coating material constituents and reaction products from the additives, is formed on the steel surfaces. The presence of this tribofilm was found to coincide with the improved tribological performance.

The aim of the present work was to add some understanding to this important area by investigating the influence of additive concentration on the tribology of DLC coatings. A conventional extreme-pressure (EP) additive was added to PAO oil at three concentrations and the friction and wear behaviour in the boundary lubrication regime was investigated. Special emphasis was put on the DLC/steel combination, which in previous investigations has shown the smoothest running-in process and a better tribological performance than the corresponding DLC/DLC and steel/steel contacts.

2. Experimental

WC-doped hydrogenated diamond-like carbon coatings (Me-C:H) with a multilayer structure of WC and a-C:H were used in this investigation. They were deposited by a reactive sputtering process with a deposition temperature of ~ 230 °C. The coatings were about 2 μm thick with a hardness of about 1200 HV. The substrate was a high-speed steel (0.9% C, 4% Cr, 5% Mo, 1% V, 2% W, 2.5% Co) with a hardness of 850 HV and surface roughness $R_a \approx 0.1$ μm.

Boundary lubricated wear and friction tests were performed in a load-scanning test rig (Fig. 1). The test configuration, involving two crossed cylinders (ϕ 10 mm, 100 mm long) allows the normal load to be gradually increased during the forward stroke and to be correspondingly decreased during the reverse stroke [20,21]. Thus, although a whole spectrum of loads is investigated, each individual point along the contact path of both specimens equal to about 1 mm will experience one unique load, also in multiple stroke tests.

The sliding speed was fixed to 0.1 m/s, the normal load covered the range between 140 and 1700 N (corresponding to maximum Hertzian contact pressures of 2.4–5.6 GPa), and the total number of strokes was 30,000. The oils investigated include pure poly-alpha-olefin (PAO; $v_{40} = 46.6$ mm^2/s), and PAO mixed with a commercial sulphur-based EP additive, at three different additive concentrations of 0.5%, 2.25% and 4.5%, respectively.

The main test series involved DLC-coated cylinders running against uncoated steel (DLC/steel). For comparative purposes, DLC/DLC and steel/steel contacts were also tested. The coefficient of friction was continuously monitored as a function of the number of cycles and within each cycle as a function of load. The wear was investigated after the test, using profilometric techniques and microscopy.

3. Results

All material combinations showed a friction that varied with the number of cycles. However, the running-in behaviour, the steady state friction level and the response to addition of additive all differed significantly between the different material combinations. The friction trends for the steel/steel combination are shown in Fig. 2, here exemplified by the behaviour recorded at a normal load of 700 N. During the first cycles in pure PAO oil, the friction coefficient was relatively high (typically 0.2–0.3), over the whole load range investigated. The level was gradually reduced during the first 40 cycles to a steady-state friction of about 0.08. Addition of the sulphur-based EP additive had practically no effect on the level of steady-state friction, as shown in Figs. 2 and 3. However, the additive reduced the number of cycles required to reach the steady state level. At the two highest concentrations tested, it was reduced to five cycles.

As expected, the addition of EP additive also reduced the wear. At a concentration of 0.5%, the EP additive only

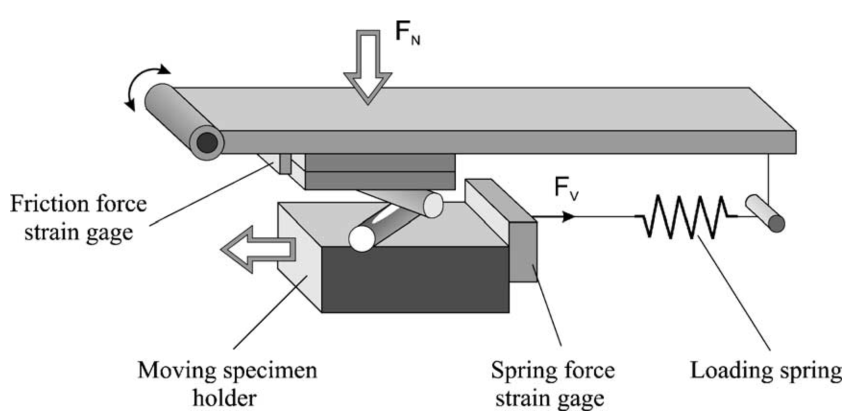

Fig. 1. Load-scanning test rig.