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Friction in a coated surface deformed by a sliding sphere

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Abstract

Stress and strain modelling and stress field computer simulations are today an important tool for systematic approach and optimisation of tribologically stressed coated contacts. Modelling illustrates and quantifies the dominating parameters resulting in crack initiation, crack growth and failure of coated surfaces. Friction and its components, adhesive and ploughing friction, are necessary input parameters in stress modelling. In Finite Element Method (FEM) modelling the ploughing component is integrated in the model while the adhesive component needs to be determined as input value for stress simulations. This paper presents how adhesive friction is determined for the TiN ($\mu_a = 0.066$) and DLC ($\mu_a = 0.047$) coatings from experimental friction measurements. The experimental value is used as an input value in the three dimensional finite element micro-model that simulates the spherical tip sliding on a DLC coated flat substrate with increasing load similar to the conventional scratch test contact. Based on the numerical contact analysis (FEM) similar friction evolution compared to the experimental friction in scratch testing was depicted. However, the analytical approach resulted in a diverse solution.

Keywords: Friction; Adhesive; Ploughing; DLC; TiN; FEM modelling

1. Introduction

Thin surface coatings are today increasingly used for improving the tribological performance of advanced products. Coatings are applied on tools and mechanical components in the production industry, on disc drives in the computer industry, on precision instruments, on lenses in optical systems and on human replacement organs. Coating deposition techniques offer a wide variety of possibilities to tailor surfaces with advanced, functional coatings. The chemical vapour deposition (CVD) and physical vapour deposition (PVD) techniques have made it possible to deposit thin coatings in a large temperature range from about 1000 °C down to room temperature. Coating materials such as TiN, TiC, Al_2O_3 and diamond-like carbon (DLC) and their combinations with multilayer structures and doping agents have been used with great success in numerous applications. In many cases, the coatings have reduced the friction and wear of components by one or two orders of magnitude. In has been shown, that even super-low friction values down to 0.001 in dry sliding can be reached with advanced DLC technology [1–5]. The deposition techniques of thin coatings and their tribological behaviour and applications have been described in several publications [6–10].

The tribological contact between two stressed surfaces in relative motion is a very complex system that is not easy to understand nor simulate or predict. The system becomes even more complex when coatings are introduced on the surfaces. The tribocontact has been studied on a macrolevel, i.e. on the component level, at microlevel, i.e. the surface asperity level, and at nanolevel, i.e. the molecular level [7,11,12]. One problem is that there is a large range of different parameters used to describe friction and wear behaviour in coated tribological contacts, some of which are not generic parameters, but directly related to experimental devices used. When modelling deformation and fracture of materials, it is crucial to use generic material parameters that describe the basic material behaviour, such as the Young's modulus in elastic deformation, the yield strength of material correlating with hardness in plastic deformation and the fracture toughness for brittle failure [13,14].

Hard layers, such as TiN and DLC, can reduce the coefficient of friction of both lubricated and unlubricated surfaces by minimising ploughing and plastic deformation in the substrate. Komvopoulos et al. [15] carried out a two dimensional FEM

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Table 1
The thickness, hardness and Young's modulus of the coatings used in the tests

Coating	Deposition method	Coating thickness (μm)	Hardness (GPa)	Young's modulus (GPa)
TiN	Magnetron sputtering	1.8	35 ± 10	475 ± 90
DLC	PACVD	0.9	5 ± 0.4	39 ± 2

analysis of friction in sliding contacts with hard coatings, such as TiN. They verified that the deformation mode at the asperity contacts depends on the layer thickness, the interfacial friction, the magnitude of the surface traction and the mechanical properties, such as Young's modulus and hardness, of the hard layer in relation to those of the substrate. With 3D FEM simulations of a sphere on a coated flat with two values of the coefficient of friction, $\mu = 0.1$ and 0.25, Kral and Komvopoulos [16] found that increasing friction has little effect on the residual groove depth, with the exception of a slight decrease in groove depth with sliding distance. The higher friction case exhibits larger front and transverse pile-up regions, indicating that increasing the coefficient of friction produces more deformation of the surface material in the sliding direction. The larger frontal pile-up region may be responsible for the decrease in groove depth with sliding distance, since a larger bow supports a larger fraction of the normal load, resulting in a slightly shallower groove.

It has been shown by FEM modelling and simulation [17] that the effect of the coefficient of friction on the deformation behaviour of elastic-plastic layered surfaces is significant for sliding contact and secondary for indentation loading. High friction loading promotes plasticity and intensifies the von Mises and first principal stresses in both the layer and the substrate, thus increasing the possibility for yielding and cracking in both the coating and the substrate. In high-friction sliding, plasticity in the substrate is affected predominately by the coefficient of friction and secondarily by the residual stress in the coating. The assessment of the situation is complicated by the "mixed" constitutive response of the system due to different materials within it, i.e. typically the linear-elasticity of the coating layer and elasto-plasticity of the substrate, and as such a single model build on a single constitutive model may not be generally adequate.

In the 3D FEM modelling and simulations of friction, stresses and deformations in the contact of a sphere sliding against a coated surface the coefficient of friction values in the range 0.08 to 0.5 have been used [17–26]. The high values of 0.5 are used in studies of the frictional heating effect while lower values in the range of 0.08–0.26 correlate with the friction during the scratch testing of a coated surface with a diamond stylus. However, there is some confusion in the literature since all authors do not clearly define if their coefficient of friction means the adhesive component, as used in modelling, or the total coefficient of friction, as received in, e.g. scratch test measurements.

The scratch test has been widely used for the adhesion evaluation of thin films [27,28]. The tangential force measured during scratching represents the friction force in scratching action. The friction values measured in scratch testing differ according to the coating type, environment and scratching parameters used, but typical values reported vary in the range 0.1–0.2 for the TiN coating on steel substrate [29] and 0.1 to 0.2 for the DLC coatings on Ti–6Al–4V substrate [30].

In this study the experimental determination of the adhesive friction component has been carried out. Based on the experimentally determined friction values numerical finite element analysis has been carried out. The results of numerical analysis will be compared to the results of analytical determination and to the experimental friction results of scratch testing.

2. Experimental

The substrate material used was power metallurgical high speed steel (HSS, Böhler S790 ISOMATRIX) with a Young's modulus of 214 GPa, Poisson's ratio of 0.29 and the strain hardening coefficient of 20. The Yield strength was estimated from ultimate bending strength of 4100 MPa. The hardness was 8.3 GPa and the samples were polished to surface roughness R_a 0.01 μm prior to deposition. Two different coating types were used in the study, namely commercial titanium nitride (TiN) coating deposited by magnetron sputtering and diamond-like carbon (DLC) coating prepared by plasma enhanced CVD process [31]. The details of the coatings are represented in Table 1.

Scratch tests were performed for the samples by the VTT scratch tester by using a diamond stylus with a spherical tip of a 200 μm radius (Rockwell C). The preload of 5 N was used and the normal force was increased continuously from 5 to 50 N during scratching. The loading rate was about 50 N/min (0.83 mm/s), sliding speed 10 mm/min (0.167 mm/s) and the scratch length was 10 mm. During scratching the tangential force representing the friction force was measured continuously. Also separate multi-pass friction measurements were performed for the coatings and for the uncoated HSS substrate by using the scratch tester in the multi-pass mode performing reciprocating movement. In multi-pass testing a static normal load of 5 and 10 N were applied and the sliding speed was 10 mm/min (0.167 mm/s). The distance of one sliding cycle was 5 mm and the sliding was performed in the same track during the 10 sliding cycles. The friction was measured during multi-pass testing continuously. After the tests the mean value of friction for each sliding cycle was calculated and this value represented the friction during one sliding cycle. The tests were performed in normal air at 50 ± 5% RH and 21 ± 2 °C.

3. Experimental results

The friction trends measured in scratch testing for TiN and DLC coated and the uncoated HSS samples are presented in Fig. 1. The scratch tests are typically carried out at least three times for one sample. The values in Fig. 1 represent the typ-