Surface & Coatings Technology 251 (2014) 283–292

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Investigation of pile-up during a rigid ball sliding on coated surface based on elastic–plastic analysis

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ARTICLE INFO

Article history:
Received 9 January 2014
Accepted in revised form 21 April 2014
Available online 28 April 2014

Keywords:
Nano-indentation
Sliding indentation
Pile-up
Finite element
Experimental test
Coating

ABSTRACT

A three-dimensional finite element model (FEM) is used to study the development of pile-up and contact situation during nano-indentation and sliding indentation of elastic–plastic coated solids. The FEM results were verified by nano-indentation and sliding indentation tests which were carried out on TiN specimens. Then, the influence of elastic–plastic deformation, penetration depth, contact friction and strain hardening on pile-up was investigated for a wide range of materials with different elastic modulus, yield stresses, strain-hardening exponents and friction coefficients. The results indicated that the pile-up/sink-in geometry depends on the relative amounts of elastic and plastic deformation characterized by (E/σ_y), in a way that pile-up grows by increasing (E/σ_y). At small non-dimensional penetration depth (h/R), the deformation is only elastic, then by increasing the load, the plastic zone grows and spreads upward and the sink-in diminishes. It was found that friction severely enhances pile-up only in small amounts of strain hardening exponent. In addition, the influence of a unified parameter on pile-up was utilized to investigate some parameters simultaneously for various strain hardenings which depicted that increasing strain hardening exponent leads to smaller pile-up. The finite element results may be used as a first estimate of the pile-up/sink-in behavior if the material parameters are known.

1. Introduction

Many situations in engineering applications involve transmission of loads over contact surfaces such as journal bearing and ball bearing assemblies, which experience sliding movements. Coatings are extensively used to improve mechanical (friction, hardness and stiffness), chemical (corrosion resistance), magnetic and electrical properties that are considerably superior from those of the substrate [1].

Coatings have been playing an important role in modern industries. Various coating deposition techniques such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) make it possible to manufacture coatings with a thickness of 1 μm, for a wide range of materials [2].

The durability of a coating highly depends on adhesion between the coating and substrate [3]. The properties that describe the failure or fracture performance, such as Young modulus, thickness and strain hardening are not so well defined and their role is unclear. Because of our limited understanding of contact phenomena most of the surface engineering development work is still based on a trial and error approach [4].

The nano-indentation and sliding indentation tests are widely used to measure the interfacial adhesion between various coating and substrate systems [5]. In a nano-indentation test, a tip made of a very hard material like diamond is pressed into the specimen whose properties are unknown. The applied load on the indenter is increased as the tip penetrates further into the specimen up to a pre-defined value in which the load may be held constant for a period or removed. Atomic force microscopy or scanning electron microscopy techniques may be utilized to image the indentation, but can be quite cumbersome. Instead, an indenter with a geometry known to high precision (usually a Berkovich tip, which has three-sided pyramid geometry) is employed [6]. The recorded values of load and penetration depth can be plotted on a graph to create a load–displacement curve. These curves can be used to extract the mechanical properties of materials [7].

During the scratch test, a diamond indenter is drawn over the surface of a coated specimen under a normal force which is increased stepwise or continuously. The increasing force has a ploughing component of friction which leads to a pile-up effect in front of the sliding tip and results in high tensile stresses. This growth of material pile-up continues until a critical normal force (F_{NC}), at which a well-defined coating failure occurs. Then, F_{NC} is taken as a criterion of adhesion between coating and substrate [8]. The schematic of sliding indentation test is illustrated in Fig. 1.

The stress distribution is one of the parameters that control the failure of the coating system during the sliding indentation process [9]. Due to

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http://dx.doi.org/10.1016/j.surfcoat.2014.04.040
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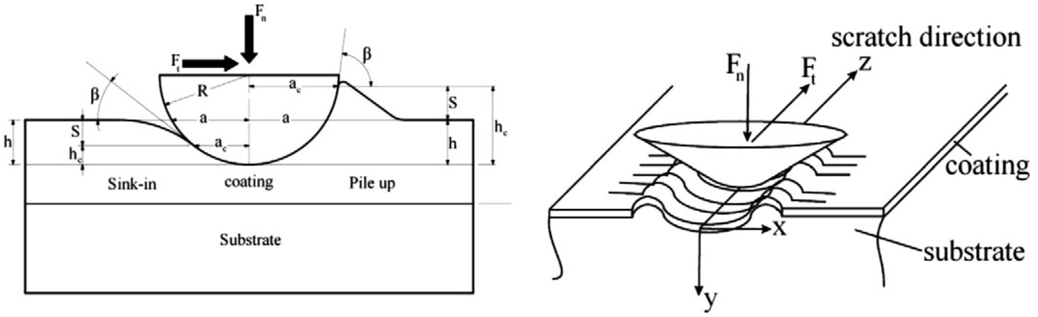

Fig. 1. A schematic illustration of scratch test.

complicated loading and friction status, as well as the nonlinear elastic–plastic behavior of the coated tribological contact, the reported works on modeling and simulation have been restricted to simplifications such as considering only elastic or plastic behavior or two-dimensional calculations. Jiang et al. [10] analyzed the frictional contact between the indenter and coating system in a sliding indentation test using 2D and 3D finite element models by ANSYS®. The indenter geometry was the same as Rockwell C where the indenter and coating were considered elastic. Bucaille et al. [6] analyzed the sliding indentation test using finite element software Forge-3®. They utilized a conical indenter with a semi-apical angle of 70.3° and the contact was assumed frictionless. The materials were considered elastic–perfectly plastic with a fixed yield strength of 1 GPa and a variable Young modulus of 2.793–2793 GPa.

The first comprehensive three-dimensional elastic–plastic model for presenting stress and strain in a typical sliding contact with a thin hard coating was presented by Holmberg et al. [2]. They illustrated how the maximum first principal stresses are generated in the tail part of the sliding contact with a diamond sphere sliding against TiN-coated steel and how a tetra-armed star-shaped stress field is generated around the contact.

In all these papers the simulations included two steps: in the first step the indenter plunges into the specimen up to a pre-defined vertical displacement to generate the normal load and then it slides horizontally on the surface of the specimen in the next step. The main objective of this research is to introduce an elastic–plastic model to study coated surfaces during nano-indentation and sliding indentation processes. After verifying the FEM model by experimental tests on a stainless steel surface coated with titanium, the influence of the elastic modulus to yield stress ratio (E/σ_y), penetration depth, friction coefficient (μ), combined effects of elasticity and depth of penetration and strain hardening (n), on stress conditions and pile-up and sink-in behavior is investigated by finite element simulations.

2. Experimental test

Nano-indentation tests were carried out by employing the depth sensing indentation (DSI) device MZT-4 (Akashi Co.). The DSI apparatus was utilized with Vickers indenter by a semi-apical angle of 68°. This system is equipped with high precision sensors that can record the ultrafine movements.

Fig. 2 illustrates a schematic display of indentation procedure that is comprised of three stages which starts by applying an initial load up to the defined maximum amount, followed by maintaining the maximum load for a limited time and accomplished by unloading.

In order to acquire accurate results, the indentation depth should not exceed more than 10% of coating thickness [11]. The obtained experimental results would be in the form of a graphical chart as Fig. 1, where L_0, L_1, h_0, h_1 and h_f are initial load, maximum load, the depth of indentation in initial load, the depth of indentation in maximum load and the depth of indentation after unloading, respectively. It is worth to note that the slope of the unloading section of the graph presents the stiffness of the material that is indicated by S [12].

The initial experiments were conducted on Cu and TiN specimens and the results are presented as graphs in Fig. 3. The loading was started with the initial amount of 0.4 mN that increased up to 25 and 10 mN for TiN and Cu, respectively. The indentation rate for both specimens was 0.01 μm/s. The steep slope of the unloading curve for Cu in comparison with TiN is attributed to less elastic recovery of Cu due to its less elastic limit.

Fig. 1 illustrates a schematic display of scratch procedure where the process parameters are defined according to Table 1. Scratch tests were carried out employing the CSEM Instruments Revetest-Scratch Tester.

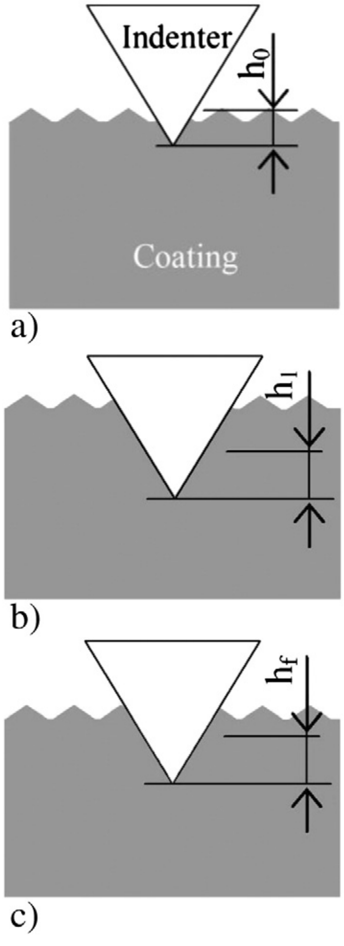

Fig. 2. The stages of indentation process: (a) initial loading, (b) maintaining load and (c) unloading.