Surface & Coatings Technology 240 (2014) 444–449

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Yield inception of a soft coating on a flat substrate indented by a rigid sphere

Wenping Song [a,b,*], Longqiu Li [a], Izhak Etsion [c], Andrey Ovcharenko [b,d], Frank E. Talke [b]

[a] Harbin Institute of Technology, Harbin, China
[b] Center for Magnetic Recording Research, University of California, San Diego, USA
[c] Department of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa, Israel
[d] Western Digital Corporation, San Jose, USA

ARTICLE INFO

Article history:
Received 1 May 2013
Accepted in revised form 30 December 2013
Available online 7 January 2014

Keywords:
Spherical indentation
Soft coating
Yield inception

ABSTRACT

The yield inception of a deformable half space covered by a soft coating and indented by a rigid sphere is studied using the finite element method. A soft coating parameter, which controls the yield behavior of this problem, is defined. Dimensionless empirical expressions for the critical load, critical contact area and critical interference at yield inception are derived as functions of the dimensionless soft coating parameter. Three different locations of the yield inception of the coated system are observed. A comparison of yield inception behavior for an uncoated substrate and substrates with soft and hard coatings is made. A minimum value of dimensionless coating thickness, which is required to protect the substrate from yielding, is proposed. It is shown that a coating with low Young's modulus and high yield strength is most desirable for protecting the substrate against yielding.

1. Introduction

With the rapid development of surface engineering technologies, soft coatings have been used as widely as hard coatings to improve the mechanical and tribological properties of components. Soft coatings, such as copper, MoS_2 and some solid lubricants, have been found useful to provide not only efficient lubrication characteristics but also low friction [1–4].

Indentation of a coated substrate by a solid sphere (see Fig. 1) has received a great deal of attention in the past. A different behavior has been reported in the literature for the elastic deformation of soft and hard coatings [5–8]. Li and Chou [5] provided a theoretical solution for the elastic stress field of a coated substrate under a parabolic load distribution, and investigated the situations of a) no coating present, b) hard coating present and c) soft coating present. They found that the radial and hoop stresses at the interface within the contact zone were tensile stresses for substrates with a hard coating and compressive stresses for substrates with a soft coating. Li and Chou [5] also proposed that both cracking of the coating and interfacial de-bonding can occur in a hard coated system, and that interfacial de-bonding is the key failure mechanism for a surface coated with a thin soft film. Matthewson [6] presented a solution for the stresses within a compliant coating on a rigid substrate during indentation by spherical and conical indenters. He found that the stress distribution was sensitive to the coating thickness and compressibility of the coating material. Later on, Matthewson [7] studied the effect of thin compliant coatings on contact stresses and found that the stresses within the coated substrate are sensitive to adhesion of the coating, Poisson's ratio and coating thickness. On the other hand, he found that the elastic modulus of the coating material was only of secondary importance. Substantially different displacements and stress distributions were observed by Schwarzer et al. [8] for substrates with hard and soft coatings, subjected to Hertzian contact pressure.

One of the main goals of this study is to determine the mechanical properties of thin film coatings [9–14]. A number of differences have been reported in the literature for indentation tests of soft coatings and hard coatings [15–18]. Pile-up around the edges of the indented material was observed during indentation tests of a soft coating on a hard substrate, e.g., copper coating on silicon substrate or tungsten coating on sapphire substrate [15–17]. However, pile-up behavior was not found to be exhibited in indentation tests of a hard coating on a soft substrate, such as, for instance, carbon nitride coating on silicon substrate [18].

All of the above investigations have demonstrated that the indentation behavior of a substrate is a function of the coating deposited on it. However, the indentation behavior of coated systems in the elastic–plastic deformation regime has been analyzed only for a limited number of material combinations, i.e., a solution is not available for the general problem of arbitrary coating parameters.

In our previous work [19], the yield inception of an indented half space with a hard coating was studied. Dimensionless empirical expressions for the critical parameters (i.e., critical load P_c, critical contact area A_c and critical interference ω_c) at yield inception were derived as functions of a dimensionless hard coating parameter. The present paper is an extension of our previous study, and deals with the case of a substrate

* Corresponding author.
E-mail address: wenping.song1985@gmail.com (W. Song).

0257-8972/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.surfcoat.2013.12.073

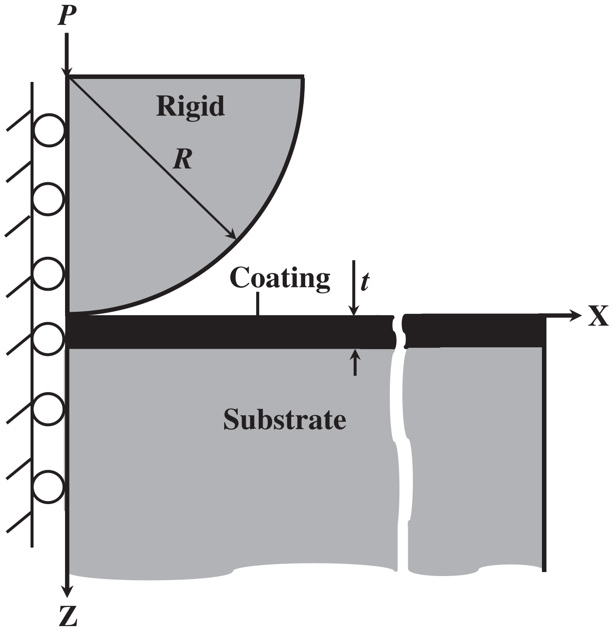

Fig. 1. Schematic of an indented coated substrate.

covered with a soft coating. The effect of coating thickness and material properties on the critical parameters of this soft coated system at yield inception will be investigated.

2. Modeling

2.1. Background

A solution for the case of an elastic sphere with radius R flattened by a rigid flat was provided by Hertz [20]. The normal load P and the contact radius a, corresponding to an interference ω, for frictionless contact condition, are given by:

$$P = \frac{4}{3}\frac{ER^{1/2}\omega^{3/2}}{(1-\nu^2)} \tag{1}$$

$$a = \sqrt{\omega R} \tag{2}$$

where E and ν are the Young's modulus and Poisson's ratio of the half space material, respectively.

The critical load P_c and the critical interference ω_c at yield inception of the sphere are [21]:

$$P_c = \frac{\pi^3}{6}C_\nu^3 Y\left(R\left(1-\nu^2\right)\frac{Y}{E}\right)^2 \tag{3}$$

$$\omega_c = \left[C_\nu\frac{\pi\left(1-\nu^2\right)}{2}\left(\frac{Y}{E}\right)\right]^2 R \tag{4}$$

where $C_\nu = 1.234 + 1.256\nu$, E, Y and v are the Young's modulus, yield strength and Poisson's ratio of the elastic–plastic sphere, respectively. In the elastic regime, Eqs. (3) and (4) are also valid for the indentation of a deformable flat by a rigid sphere.

In Ref. [19], two dimensionless parameters were found to control the yield inception of an indented system with a hard coating. They are the so-called modified critical interferences ratio

$$\kappa' = \left(\omega_{c_{co}}/\omega_{c_{su}}\right)/(E_{co}/E_{su}) \tag{5a}$$

and the hard coating parameter

$$\lambda_h = \left(\frac{t}{R}\right)\left(\frac{P_{c_{co}}}{P_{c_{su}}}\right)^{-0.51}\left(\frac{E_{su}}{Y_{su}}\right)^{0.963} \tag{5b}$$

Fig. 2 (taken from Ref. [19]) presents typical results for the modified dimensionless critical load of the indented system with a hard coating. A peak value of the modified critical load $(P_c/P_{c\_co})/(P_c/P_{c\_co})_{max}$ was observed at $\lambda_h = (\lambda_h)_p = 2.046$, where $(P_c/P_{c\_co})_{max}$ is the maximum value of the dimensionless critical load ratio. A comparison with the results presented by Goltsberg et al. [22] for yield inception of a flattened coated sphere showed that the behavior of these two cases was very similar.

2.2. Finite element model

Fig. 3(a) presents a 2D axisymmetric finite element model of a coated half space indented by a rigid sphere (see Fig. 1). This finite element model is similar to that developed by Song et al. [19]. The Young's modulus of the sphere was chosen to be $E_{sphere} = 1000E_{co}$ to simulate a "perfectly rigid" body. Using such an approach for the simulation of a rigid sphere reduces substantially the computing time.

The simulation was performed using a commercially available finite element software (ANSYS, version 11.0) with an implicit integration solver. The dimensions of the substrate were chosen to be $4R \times 4R$ in the x and z directions, respectively. Such dimensions are much larger than the radius of the contact area given in Eq. (2) and hence, the boundaries of the selected substrate are far enough from the contact zone and do not affect the stresses in that zone.

As shown in Fig. 3(b), the coated substrate was divided into three different mesh density zones. Zone I, with a distance of $0.008R$ from the z-axis, contained the entire contact area as well as the zone where yield inception occurred. Zone I had the finest mesh and the typical length in the x direction of the element was kept approximately $(4 \sim 8) \times 10^{-5}R$ to capture accurately the contact area. The subzones II and III, outside the contact zone, had a gradually coarser mesh with increasing distance from the contact zone.

An eight-node quadrilateral element (PLANE183) was used for both the sphere and the coated substrate. A three-node contact element (Conta172) and a target element (Targe169) were used for the contact surfaces of the sphere and the coating, respectively. The entire model consists of approximately 20,000 elements and 60,000 nodes depending

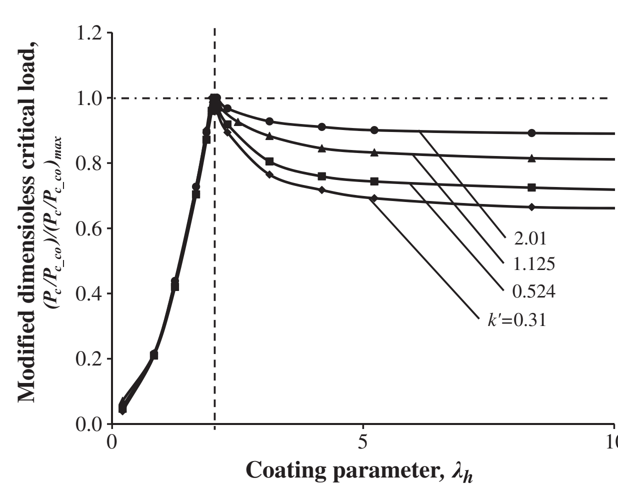

Fig. 2. Modified dimensionless critical load $(P_c/P_{c\_co})/(P_c/P_{c\_co})_{max}$ of an indented system with a hard coating as a function of the hard coating parameter λ_h for different values of k' (Song et al. [19]).