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Dynamic frictional contact problems involving elastic coatings

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ABSTRACT

This paper presents a general theory of dynamic frictional contact of elastic coatings pressed against by a rigid punch moving with a constant speed. Governing equations of elastodynamics are solved by applying Galilean and Fourier transformations. The contact problem is then reduced to a singular integral equation, which is solved numerically. Developed procedures are verified through comparisons made to the available computational and analytical results. Parametric analyses illustrate the influences of punch speed, material and geometric parameters, and friction on contact stresses. Especially at higher punch speeds, the difference between contact stress magnitudes obtained through elastostatic and elastodynamic solutions is rather significant. A formulation based on the elastodynamic theory is required to compute contact stresses generated in such problems.

1. Introduction

Prolonging lifetime of machinery is necessary to meet the demands of growing industrialization. Scientists have been trying to develop methods to control or reduce surface wear since it is one of the important factors affecting machine life. One common way of controlling surface friction and wear has been utilization of surface treatments. Major failures in machine components originate from the surface and thus surface related phenomena such as wear, fatigue, and corrosion play critical roles in lifetime, performance and maintainability of machinery. Mechanical components like sliding bearings, cams, shafts, valves and cutting tools today face higher performance requirements. Coated surfaces are useful in improving mechanical properties such as stiffness, strength, fatigue life and resistance against wear. The use of surface coatings opens up the possibility for material designs that enable specific properties at locations where they are most needed [1]. Different types of coatings, and their fabrication processes and future applications are reviewed by Hogmark et al. [2]. In this study, primarily coatings processed by physical vapor deposition (PVD) and chemical vapor deposition (CVD) are considered. It is reported that most commercial CVD and PVD coatings are manufactured as a single layer consisting of a single structured phase. The most common CVD and PVD coatings are nitrides and carbides, among which we can mention TiC, TiN, CrN, W2C and WC/C. They are usually applied directly to the surface of a homogenous substrate material. Since major failures originate from surface related damages, the identification of contact stresses is important in design of coated structures. Contact mechanics is a theoretical and applied framework that is commonly employed to study behavior of surface coatings in contact with external agents.

First studies on contact mechanics were carried out by Hertz [3] in 1882. Some benchmark solutions are provided by Johnson [4]. Early work on contact mechanics focus on contact mechanics of homogeneous and layered materials. Formulations outlined in most of these studies are based on the elastostatic differential equations. A wide variety of punch profiles and contact geometries are considered, and related contact stresses are presented. Stress and deformation fields in half-space and layered elastic media are given by Ling et al. [5]. Pressure distribution for a rigid cylinder indenting an elastic layer on a rigid substrate was determined analytically by Meijers [6], while Chiu and Hartnett [7] examined the pressure distribution on an elastic substrate. Gupta and Walowit [8] calculated stress distributions for both elastic and rigid cylinders that are in contact with coatings bonded to elastic substrates. The contact problem between several elastic layers and a parabolic counter-face was solved by Chen and Engel [9]. Cylinder and cylinder contact, either one or both coated, and either one or both with elastic or rigid substrates was examined by Solecki and Ohgushi [10]. Komvopoulos et al. [11] investigated the contact between a rigid surface and a layered structure by the finite element method.

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Nomenclature

x, y	Axes of the stationary coordinate system
X, Y	Axes of the moving coordinate system
V	Punch speed
t	Time
P	Normal force applied by the punch
Q	Tangential force applied by the punch
η	Coefficient of friction
a	End point coordinate of the flat punch
b	End point coordinate of the triangular punch
$\mu_1,\ \mu_2$	Shear moduli of the coating and the substrate
$\nu_1,\ \nu_2$	Poisson's ratios of the coating and the substrate
$\rho_1,\ \rho_2$	Mass densities of the coating and the substrate
$\kappa_1,\ \kappa_2$	Kolosov's constants of the coating and the substrate
$u_1,\ u_2$	Horizontal displacement components in the coating and the substrate
$v_1,\ v_2$	Vertical displacement components in the coating and the substrate
h_1	Coating thickness
h_2	Substrate height in the finite element model
l_m	Substrate length in the finite element model
l_p	Flat punch width in the finite element model
$c_{s,1},\ c_{s,2}$	Shear wave propagation speeds in the coating and substrate
$c_1,\ c_2$	Dimensionless speeds for the coating and the substrate
$\sigma_{1YY},\ \sigma_{2YY}$	Normal stresses in the coating and the substrate
$\sigma_{1XX},\ \sigma_{2XX}$	Lateral stresses in the coating and the substrate
$\sigma_{1XY},\ \sigma_{2XY}$	Shear stresses in the coating and the substrate
λ	Fourier transform variable
$M_j(\lambda),\ R_k(\lambda)$	Unknown functions appearing in displacement expressions ($j = 1, \ldots, 4$; $k = 3,4$)
$N_j(\lambda)$	The function appearing in the horizontal displacement component expression ($j = 1, \ldots, 4$)
s_m	Roots of the characteristic equation ($m = 1, \ldots, 4$)
$k_{11},\ k_{12},\ k_{21},\ k_{22}$	Kernels of the integral equations
$e_{ij},\ f_{ij},\ g_{ij},\ h_{ij}$	Leading terms of asymptotic expansions ($i = 1,2;\ j = 0$)
ϕ_{ij}	Functions that appear in the kernels ($i, j = 1,2$)
$s,\ r$	Normalized coordinates that vary between -1 and 1
l	Half of contact zone length
$\Theta(r)$	Solution of the integral equation in normalized coordinates
c_n	Unknown coefficients in contact stress expansion
$W(r)$	Weight function
$P_n^{(\alpha,\beta)}(r)$	Jacobi polynomial of order n
$\alpha,\ \beta$	Strengths of the stress singularities
$Z_{1n},\ Z_{2n}$	Bounded terms of the integral equation
K_I	Normalized stress intensity factor
v_0	Constant indentation depth by the rigid flat punch
θ	Inclination angle of the triangular punch
σ_0	Average stress in the contact region
$\varepsilon\%$	Percent difference between the elastostatic and elastodynamic results

Contact mechanics of coated structures has also been studied extensively, due to common applications of protective coatings in various fields of technology. These articles on coated and layered media demonstrate influences of factors such as coating stiffness, coefficient of friction, and contact geometry upon the contact stresses. A two dimensional frictional sliding contact problem between a rigid indenter and a hard coating-substrate system was examined by Kulchytsky-Zhyhailo and Rogowski [12]. Bragallini et al. [13] used strain approach for design of coated contacts and some results were provided for soft and hard coatings. Contact damage mechanism in TiN coatings on steel substrates was investigated by Bhowmick et al. [14]. Finite element method is used to examine yielding behavior of hard coatings under sliding contact [15], and contact mechanics of transversely isotropic coatings [16]. Contour plots of the contact stress in a coated half-space under Hertzian pressure distribution were provided by Schwarze et al. [17]. Finite element modeling of monolayer and multilayer coatings was performed by Kot [18]. Fretigny and Chateauminois [19] calculated displacement and stress fields within isotropic layered media in frictionless contact with a rigid axisymmetric punch. The frictional sliding contact problem between a spherical indenter and a layered elastic half-space was examined by O'Sullivan and King [20]. The contact problem between a rigid flat punch and a sphere possessing a relatively thin hard coating is solved by Goltsberg and Etsion [21].

In recent years, researchers carried out various studies on elastostatic contact mechanics of advanced materials including anisotropic and functionally graded materials. These articles draw a clear picture of elastostatic contact conditions and include results illustrating the effects of material and geometric parameters on contact stress magnitudes and other related quantities. However, almost all of this new work seem to exclusively focus on elastostatic contact. Chidlow and Teodorescu [22] developed an analytical technique to examine sliding contact problems of inhomogeneous materials comprising a coating-transition layer-substrate and a rigid punch. Alinia et al. [23] solved the sliding contact problem between a functionally graded coating and a rigid punch and provided through the thickness stresses. The sliding contact problem for an orthotropic coating bonded to a substrate was studied by Alinia et al. [24]. Fully coupled partial slip contact problems of orthotropic materials were investigated by Alinia and Guler [25]. A simplified analysis procedure for 2D sliding frictional contact between rigid indenters and FGM coated substrates was developed by Jobin et al. [26]. Liu et al. [27] analyzed partial slip behavior of a functionally graded piezoelectric coating attached to a piezoelectric substrate. An axisymmetric contact problem between a conical indenter and a half-space with a functionally graded coating was solved analytically by Vasiliev et al. [28]. Analytical and finite element solutions for the plane contact problem of a rigid cylindrical punch sliding on a graded orthotropic half-plane were presented by Guler et al. [29]. Arslan and Dag [30] developed analytical and computational methods to solve contact mechanics problems involving a rigid punch of an arbitrary profile and an orthotropic graded coating. Results provided in these articles provide valuable insight into the behavior of advanced materials subjected to elastostatic contact. However, in sliding contact problems involving a relatively higher punch speed, exclusion of the dynamic effect will not result in mathematical models representative of the actual physics of contact conditions. Thus, new developments are needed to reveal material behavior under elastodynamic contact loading.

There are a few studies that consider dynamic effects resulting from punch motion. Zhou et al. [31] investigated the influence of punch speed on frictionless dynamic contact between a moving punch and an orthotropic half-plane. Zhou et al. [32] solved a similar dynamic half-plane problem by including friction. The dynamic behavior of a frictional punch moving over the surface of an anisotropic material was