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Semi-analytical model for rough multilayered contacts

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ABSTRACT

This paper presents a new model for analysis of non-conformal rough surface contacts where one or both of the contacting bodies are coated with a multilayered coating. The model considers elastic contact of arbitrary geometry with real measured roughnesses and both normal and tangential surface loads. It predicts contact pressure distribution, surface deformations and full subsurface stress field. As such, the model offers an optimisation tool for analysis and development of multilayered coatings. Influence coefficients approach is utilised to obtain contact pressures and subsurface stresses while the contact solver is based on a standard conjugate gradient method. To improve model efficiency, a semi-analytical approach is devised, where the influence coefficients for displacements and stresses are expressed explicitly by solving the fundamental equations in the frequency domain. Fast Fourier Transforms in conjunction with discrete convolution are then utilised to provide the solution in spatial domain. Selected results are presented to first validate the model and then illustrate the potential improvements that can be achieved in the design of multilayered coatings through application of the model.

1. Introduction

Surface coatings are widely employed in tribological components with the primary aim of protecting contacting surfaces from damage and/or reducing friction, particularly under poor lubrication conditions. Bearings, piston rings, fuel injectors and cams and followers are some of the mechanical components which were of tribological coatings and are often employed. Relative to a homogenous contact, the presence of a coating in general modifies the contact mechanics in two ways: contact pressures and areas are either increased or decreased depending on the coating properties relative to the substrate and the subsurface stress fields are modified not least due to the mismatch in elastic properties of the coating and the substrate. When carefully controlled, such changes can offer superior contact performance but when poorly understood they can lead to premature failure of coated contacts through mechanisms that may not have been expected in the equivalent homogenous contact, such as fracture, fatigue and delamination. Many modern coatings possess a multilayered structure, where the properties of each coating layer can be chosen to optimise the prevalent contact mechanics for improved tribological performance of the overall coating in terms of reduced friction and wear and extended durability. Such multilayered structures can therefore offer advantages over a single layer coating, but they also produce even more complex contact stress fields which need careful consideration. Accordingly, to maximise the benefits offered by multilayered coatings as well as minimising the risk of unexpected failures through undesirable stresses, a contact model which is able to predict contact pressures, deformations and subsurface stresses in rough multilayered contacts is needed.

The earliest contact model for coated surfaces was that of Burmister [1] who, as part of his studies into airport runway surfaces, produced a model for three-dimensional, single layered, smooth contacts subject to normal load. Over the following half a century several authors produced single-layered models capable of dealing with various levels of complexity. Dundurs [2] considered a smooth two-dimensional contact of coated surfaces and proposed two non-dimensional parameters to describe the material mismatch between the coating and the substrate. Gupta and Walowit [3] utilised Fourier transforms of Airy stress functions to provide a solution for deformations and stresses in a coated contact subject to unit pressure loading at the origin, which can then be utilised as an influence function for the said contact. O'Sullivan and King [4] included both normal and tangential loading in an influence coefficient based model, while Komvopulos and co-workers [5] used finite element methods to study a similar contact configuration. Nogi and Kato [6], Kannel and Dow [7] and Cole and Sayles [8] provided full contact solutions for a layered contact of rough surfaces while others, such as Kadiric and co-workers [9], Ju and Chen [10] and Leroy et al. [11] also considered in-contact thermal effects of the coating.

In recent years the layered contact analyses have been extended to include multilayered coating systems. Chen [12] used Fourier integrals to extend the single layered model of Burmister [1] to smooth bodies containing up to two layers. Elsharkawy and Hamrock [13] utilised the

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Nomenclature

A_w Influence coefficient matrix for surface displacements, $W_{\eta=0}$
A_s Influence coefficient matrix for general stress, S
$A^{(k)}$, $B^{(k)}$, $C^{(k)}$, $D^{(k)}$, $F^{(k)}$ and $H^{(k)}$ Solution constants. Superscript (k) indicates the layer
$E^{(k)}$ Young's modulus for layer k (Pa)
$E^{*(1)}$ Equivalent elastic modulus based on properties of counter-face and layer (1), $E^{*(1)} = \left(\frac{1-\nu^2_{counterface}}{E_{counterface}} + \frac{1-\nu^{(1)2}}{E^{(1)}}\right)^{-1}$
$K^{(k)}$ $K^{(k)} = -\frac{\lambda^{(k)}+3\mu^{(k)}}{E^{(k)}(\lambda^{(k)}+\mu^{(k)})}$
L Load (N)
P_{Hertz} Maximum Hertz pressure (Pa)
S Stress (Pa)
U, V, W Normalised displacements, u/l, v/l, w/l respectively in x-, y-, z- direction
a_{Hertz} Hertz contact semi-width
f_r Friction coefficient
$h^{(k)}$ Thickness of layer k (m)
i $\sqrt{-1}$
l Semi-width in x and y directions of the surface discretisation patch (m)
n Number of layers, excluding the substrate
p Contact pressure (Pa)
s, r Fourier transform variables for ξ and γ directions respectively
x, y, z Spatial coordinates (m)
$\alpha_D = \frac{\Gamma(\kappa_S+1)-(\kappa_L+1)}{\Gamma(\kappa_S+1)+\kappa_L+1}$, $\beta_D = \frac{\Gamma(\kappa_S-1)-(\kappa_L-1)}{\Gamma(\kappa_S+1)+\kappa_L+1}$ Dundurs' parameters where $\Gamma = \frac{E_L(1+\nu_S)}{E_S(1+\nu_L)}$, $\kappa_S = 3-4\nu_S$, $\kappa_L = 3-4\nu_L$(subscripts 's' and 'L' indicate substrate and coating in a single layered coating system).
β $\sqrt{s^2+r^2}$
ξ, γ, η Normalised spatial coordinates; x/l, y/l and z/l
$\lambda^{(k)}$ Lame's first constant $\left(=\frac{E^{(k)}\nu^{(k)}}{(1+\nu^{(k)})(1-2\nu^{(k)})}\right)$ for layer k, (Pa)
$\mu^{(k)}$ Lame's second constant $\left(=\frac{E^{(k)}}{2(1+\nu^{(k)})}\right)$ for layer k, (Pa)
$\nu^{(k)}$ Poisson's ratio for layer k
σ_{ij} Stress tensor (Pa)

Subscripts

i, j, k, l, m Indices of the mesh positions in the discretised 3D domain
t loop counter in the iterative process

Superscripts

(k) Indicates the coating layer k

Other symbols

$\approx$ when placed over variable symbol, indicates double Fourier transformed variable in ξ and η directions
Δ Biharmonic operator $=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$

Gupta and Walowit [3] solution to develop a model for a dry, sliding contact between two elastic bodies coated with a number of thin layers, both bodies possessing the same layer system. Their model is limited to two-dimensional contacts of two ideally smooth bodies while results are presented for contacts with up to two coating layers. A similar approach to that presented in this paper was used by Plumet and Dubourg [14], where the influence coefficients were first obtained for a multilayered contact in frequency domain by utilising Fourier transforms. Their method is limited to two smooth bodies, one of which is rigid and elliptical, while the presented results consider single-layered systems only. Cai and Bhushan [15,16] considered one and two layered systems utilising Papkovich–Neuber potentials to obtain influence coefficients and minimum complimentary energy principle to obtain the contact solution. They present results focusing on the effect of the material properties of the intermediate layer in a two layered coating.

It is worth noting that in parallel to coated contacts, contacts of functionally graded materials (FGM), another class of inhomogeneous materials where material properties vary continuously with depth instead of having distinct layer interfaces, have also received attention in the literature. Giannakopoulos and Pallot [17] and Ke and Wang [18,19], amongst others, produced two dimensional models for smooth contacts of FGM materials where Young's modulus varied continuously with depth. Choi et al. [20] on the other hand used finite element methods to model plastic indentation of smooth plastically graded materials.

From the discussion above it is evident that the existing multilayered contact models all suffer from one or more limitations in terms of either the number of layers they consider (generally one or two), the type of loading (commonly limited to normal load only) and/or the contact geometry (often only two dimensional line contacts or smooth bodies are considered). The current model attempts to address these deficiencies by providing an efficient semi-analytical contact model that considers two elastic bodies with any number of coating layers, normal and tangential loading, real rough surfaces and arbitrary (non-conformal) contact geometry. With the aim of illustrating the