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Semi-analytical solution of three-dimensional steady state thermoelastic contact problem of multilayered material under friction heating

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A R T I C L E I N F O

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A B S T R A C T

Multilayer coatings offer a possibility to design the surface according to the different requirements, which attracts intense attentions from engineering and research community. The coupled thermo-mechanical contact problem of a multilayered material is of great interest. This paper firstly derives the frequency response functions (FRF) of thermoelastic fields through thermoelastic governing equations. The unknown coefficients in the FRFs are assembled in a linear system of matrix equations according to the thermal and mechanical loadings on surface and continuity condition of heat flux, temperature, displacement and stresses at each interface; then the coefficients are solved and expressed recursively. Based on the closed-form solution of FRFs, a fast semi-analytical method (SAM) is developed to solve the three-dimensional thermoelastic contact problem involved in arbitrary multilayered materials. There are no limits on the number or the thickness of layers, and material parameters can be varied arbitrarily. The present model is verified by literature and FEM and shows a high robustness and efficiency. Thermoelastic contact of multilayered materials with different coating designs under friction heating is further studied and the thermal effect is explored.

1. Introduction

Coating/substrate system and functionally graded materials (FGMs) are increasingly used in a wide range of applications. One important application is in tribological systems. For such materials, the material properties usually vary along the depth direction to obtain the good mechanical and/or thermal performance. Used as coatings or interfacial zones, multilayered materials and FGMs can reduce the magnitude of residual and thermal stresses, mitigate stress concentration and increase fracture toughness [1]. Many researches have been carried out experimentally and theoretically to understand the mechanical/thermal behaviors of multilayered material based on deformation and stress analyses with different methods, such as finite element method (FEM) [2–4], boundary element method [5,6] and the semi-analytical method (SAM) [7–9], in which the thermal effect is not considered. However, in many cases a significant amount of frictional heating may be generated due to the frictional sliding between the two contacting bodies, which in turn leads to the thermoelastic distortion and contact damage at the contacting surface [10]. At the same time, temperature rise shows a significant effect on metallurgical microstructure, thermal shrinkage, thermal cracking, residual stresses, and chemical modifications, which greatly influence the performance and reliability of the components [11]. Although the contact problem in multilayered materials is extensively investigated, very limited literature are available concerning its thermo-mechanical coupling effect in the three-dimensional conditions.

Barber et al. [12–14] is devoted to the study of thermoelastic contact problem in the past decades, mainly focused on homogeneous material and the related instability. With coating/substrate system being increasingly concerned, FGMs are investigated by many researchers. Choi and Paulino [15] analyzed the thermoelastic contact problem between a rigid flat punch and FGM. Similarly, Barik et al. [16] studied the steady state thermoelastic contact in FGMs by numerically solving a system of singular integral equations, and Myslinski [17] investigated the thermoelastic rolling contact problems in FGMs through Faedo-Galerkin approach. Ke et al. [10,18] studied two-dimensional thermoelastic contact problem of FGMs with exponentially and arbitrarily varying properties. Different with others, Chen et al. investigated the thermo-contact mechanics of a rigid cylindrical punch sliding on a graded layer in finite thickness [19,20] and the frictional contact of a rigid punch on an arbitrarily oriented gradient half-plane [21]. However, the variations of material properties are very limited in their work and the continuity of material parameter of two adjacent layers is required. In addition, most of their work are focused on the two-dimensional (plane strain) or axisymmetric problems, and the general three-dimensional problem is not involved. Although Shi [22]

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Nomenclature

a_0	contact radius in the Hertz solution of the substrate material
$A_i^{(j)}$, $B_i^{(j)}$, $M_i^{(j)}$	unknown coefficients in solution of thermoelastic fields of jth layer in frequency domain
b_j, d_j, K_j, υ_j	intermediate variables about material properties
$C_i^{(j)}$, $D_i^{(j)}$, $k_{il}^{(j)}$	intermediate variables (defined in Appendix) in recursive solution
$g_i^{(j)}$, $N_a^{(j)}$, $N_b^{(j)}$, $s^{(j)}$, $S_i^{(j)}$, $\beta_i^{(j)}$	intermediate variables (defined in Appendix) in recursive solution
E_j^*, E_j	elastic modulus of layer j, [MPa]; $E_j = E_j^*/E_{L+1}^*$
f	friction coefficient
$F^{(j)}$, $H^{(j)}$	intermediate variables for solving governing equations
G_j	shear modulus of layer j, [MPa]
h_j^*, h_j	thickness of layer j, [m]; $h_j = h_j^*/a_0$
i	pure imaginary, $\sqrt{-1}$
L	number of layers in multilayered material
p, q, Q	normal, shear and thermal loadings in spatial domain
$\tilde{p}$, $\tilde{q}$, $\tilde{Q}$	normal and shear loadings in frequency domain
p_0	peak contact pressure in the Hertz solution of the substrate material [MPa]
T	dimensionless temperature rise; $T = T^*/T_0$, $T_0 = fVp_0a_0/\kappa_{L+1}^*$
$u_i^{(j)}$	displacement $u_i$in layer j, [m]
V	sliding velocity of indenter, [m/s]
$\boldsymbol{w}$	surface gap between ball and multilayered material, [m]
W	normal load on the indenter
x^*, y^*, z^*	cartesian coordinates in the spatial domain, [m]
x, y, z	Dimensionless cartesian coordinates in the spatial domain, $x = x^*/a_0$, $y = y^*/a_0$, $z = z^*/a_0$
X	submatrix in matrix equations
α_j	thermal expansion coefficient of layer j, K^{-1}
κ_j^*, κ_j	conductivity of layer j, W/(m K); $\kappa_j = \kappa_j^*/\kappa_{L+1}^*$
λ_j	Lame constant of layer j, $\lambda = E\nu/(1+\nu)/(1-2\nu)$
ν_j	Poisson's ratio of layer j
$\sigma_{ik}^{(j)}$	stress component σ_{ik} layer j, [MPa]
ω_x, ω_y, ω	variables in frequency domain corresponding to the x and y, $\omega = \sqrt{\omega_x^2 + \omega_x^2}$

Special marks

$\sim$	double Fourier transforms operations
$\dot{\sim}$	double Fourier transforms and derivative with respect to z

studied the three-dimensional thermoelastic contact problem in layered half-space, only single layer with/without an intermediate layer is considered.

It is of the great convenience for applications to develop explicit expressions of frequency response functions (FRFs) to avoid the tedious numerical procedures [7]. Through FRFs and DC-FFT (discrete convolution and FFT) [23], Liu et al. solved the thermoelastic stress fields [24] and the thermoelastic contact problem [25] in homogeneous half-space. Then through recursive method, Yu and Wang [7,26] derived the explicit FRFs for the stress and displacement fields in multilayered material, and studied the (fretting) contact problem. However, the thermal effect is not taken into account. The matrix equation and similar recurrence relationship are constructed by Jain et al. [27], who studied the two-dimensional heat conduction in spherical coordinates

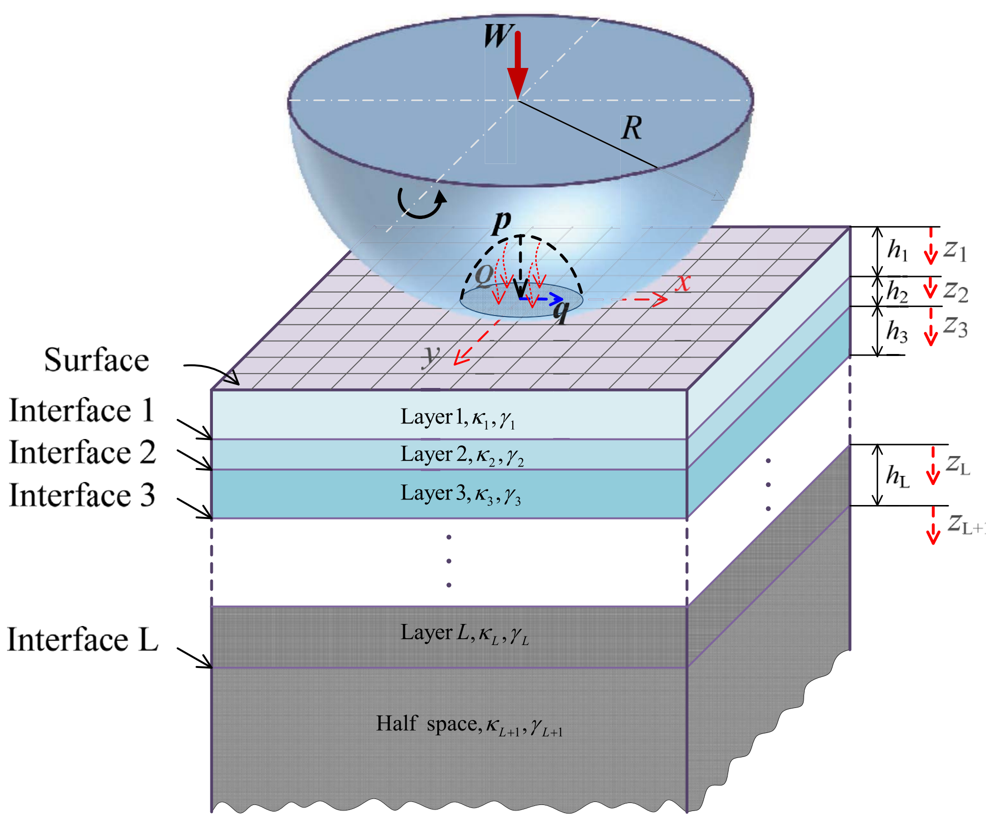

Fig. 1. Schematic of thermoelastic contact of multilayered material with a rigid ball.