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Transient thermo-electro-elastic contact analysis of a sliding punch acting on a functionally graded piezoelectric strip under non-Fourier heat conduction

Yue-Ting Zhou[a,*], Chuanzeng Zhang[b,**], Zheng Zhong[a], Lihua Wang[a]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai, 200092, PR China
[b] Department of Civil Engineering, University of Siegen, D-57068 Siegen, Germany

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ABSTRACT

Within the framework of the non-Fourier heat conduction law, this paper presents a transient, frictional thermal analysis with heat generated by a sliding punch acting on the surface of a functionally graded piezoelectric strip (FGPS). A continuous variation in the thickness direction is adopted for the material properties of the piezoelectric strip. By using the Laplace and Fourier integral transform techniques and the superposition principle, general solutions of the thermal field, and homogeneous solutions for both real and complex eigenvalues and particular solutions for the electro-elastic field are given. Results in the time-domain are obtained by applying the numerical Laplace-transform inversion method, and the convergence behavior is analyzed. Numerical results demonstrate that the thermal relaxation effect makes the results of the non-Fourier heat conduction model reach their peak values later than those of the Fourier model. The effects of the punch velocity, the friction coefficient, and various gradient parameters on the contact stress and the surface heat flow are revealed in details.

1. Introduction

To account for the energy transfer by the heat conduction, the classical Fourier law has been widely used in engineering applications (Özisik, 1993). The Fourier heat conduction equation is of parabolic type, which allows the thermal disturbances to spread at an infinite thermal wave propagation speed and needs to be modified at the very small length and time scales in some nano- or micro-scale systems (Chen and Hu, 2012). A popular approach is to take the finite velocity of the thermal wave propagation into account with the concept of the relaxation time introduced. This modification turns the heat conduction equation from a parabolic type to a hyperbolic one (Cattaneo, 1958; Vernotte, 1958; Tzou, 1995). Various hyperbolic heat conduction models were proposed previously, such as the Cattaneo-Vernotte (C-V) model (Cattaneo, 1958; Vernotte, 1958), the thermomass model in dielectrics (Guo and Hou, 2010), and the dual-phase-lag model (Tzou, 1995). In the solution for the temperature response in a finite thin film under the action of a time-varying and spatially-decaying internal heat source, Lam (2013) revealed the differences among these three models and the classical Fourier model, and concluded that the selection of a proper thermal model is essential to grasp accurately the thermal behavior in advanced composite materials. Functionally graded materials (FGMs) are a special kind of composite materials, wherein the gradual composition variations of the material constituents from one surface to another improve their thermal properties suitable for high-temperature environments. Sharma and Mishra (2017) concerned the free vibrations of a functionally graded sphere within the framework of the generalized thermoelasticity with a relaxation time, and investigated the influences of the grading or gradient parameters on the frequency shift and the thermoelastic damping due to the Fourier and non-Fourier processes of the heat conduction.

Extreme thermal environments should be carefully addressed when designing sliding contact systems in which the frictional heating, thermal deformation and elastic contact may lead to severe disturbances of the mechanical and temperature fields like the localized high-temperature contact regions (Anderson and Knapp, 1990). Barber and co-authors (Hills and Barber, 1985; Lee and Barber, 1993; Barber, 1999) investigated comprehensively the frictional heat generation because of the sliding contact, and found that the frictionally generated temperature rise may greatly affect the performance of the contact system and even make it unstable. In recent years, researchers exploited the potential of using functionally graded materials (FGMs) to improve the tribological performance of the mating components and enhance the stability of the contact system. Choi and Paulino (2008) considered the thermoelastic contact of a functionally graded sandwich with the heat generated by a sliding flat punch, and pointed out that the three-

* Corresponding author.
** Corresponding author.
E-mail addresses: zhouyueting@yeah.net (Y.-T. Zhou), c.zhang@uni-siegen.de (C. Zhang).

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layer coated system with a graded interlayer tends to be stronger to resist the contact damage when compared with the two-layer graded coating/substrate system. Chen et al. (2012) examined the thickness size-effect on the contact stress of an FGM with a frictional heating generated by a rigid cylindrical punch. Using the homogeneous multi-layer model to approximate the arbitrarily varying material properties of the FGM coating, Liu et al. (2012) investigated the thermoelastic contact of an FGM coated half-plane with a rigid punch sliding over its surface, and compared the results with those of Choi and Paulino (2008). Recently, Kulchytsky-Zhyhailo and Bajkowski (2015) addressed the axisymmetrical thermoelastic problem of a functionally graded coated half-space with its surface heated in a circular area. Balci et al. (2016) proposed a finite element method (FEM) based procedure for the thermoelastic analysis of the FGM coatings under the frictional contact with the heat generation. When the conductive heat transfers between two contact bodies, thermoelastic instability may occur. Mao et al. (2014, 2015) examined the thermoelastic instability between an FGM layer and a homogeneous solid with infinite or finite size. In these previous studies on the frictional heat generation and thermoelastic instability, the heat conduction is described by the classical Fourier law. How the non-Fourier law will affect the frictional heat generation attracts increasingly many researchers' attention. Moreover, with a new kind of novel smart materials named functionally graded piezoelectric materials (FGPMs) (Ke et al., 2008, 2010; Su et al., 2016) appearing which possess combined advantages of the piezoelectric materials (Karapetian et al., 2005, 2009) and FGMs, it requires researchers pay attention to frictional heat generation of functionally graded piezoelectric materials.

Motivated by the above-mentioned reasons, this study performs a frictionally generated heat conduction analysis for a functionally graded piezoelectric strip subjected to a sliding punch loading based on the non-Fourier heat conduction law. The thermo-electro-mechanical properties of the functionally graded piezoelectric strip, such as the thermal conductivities, elastic constants, piezoelectric constants and dielectric permittivities, temperature-stress coefficients and temperature-electric displacement coefficient, vary continuously along the thickness direction. To solve the time-dependent problem for the temperature and elastic fields, the Laplace transform and its numerical inversion are used. The transient thermo-electro-elastic contact behaviors are investigated by changing various material parameters to show the influences of the non-Fourier heat conduction and the differences between the Fourier and non-Fourier heat conduction laws.

2. Problem statement and formulation

Fig. 1 shows a functionally graded piezoelectric layer with the thickness L, which is fixed on a rigid foundation. A rigid insulated flat punch with the width $2c$ moves with a constant velocity S_0 with a Cartesian coordinate system xoz attached. On the surface $z = 0$, a normal force P and a frictional tangential force Q in the contact region are acting, which are related by the Coulomb-type law $Q = \mu_0 P$ with μ_0 being the constant friction coefficient.

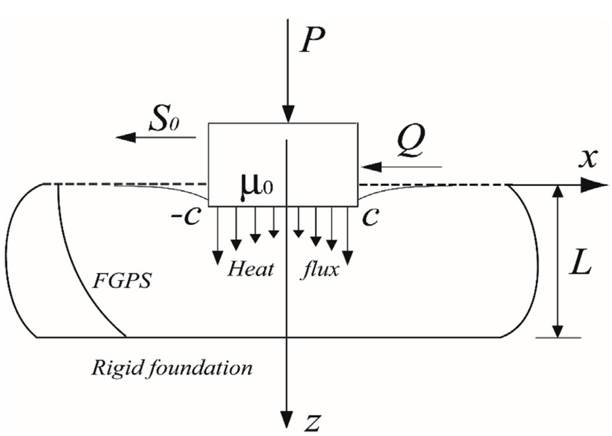

Fig. 1. Frictional heat generated by a punch sliding over the surface of a functionally graded piezoelectric strip (FGPS).

2.1. Basic equations

The functionally graded piezoelectric layer has the following continuous thermo-electro-elastic properties:

$$k_j(z) = k_{j0}\exp(\delta z/c), \tag{1}$$

$$[c_{jl}(z),\ \ e_{jl}(z),\ \ \varepsilon_{jj}(z)] = [c_{jl0},\ \ e_{jl0},\ \ \varepsilon_{jj0}]\exp(\beta z/c), \tag{2}$$

$$[\lambda_{jj}(z),\ \ g_{33}(z)] = [\lambda_{jj0},\ \ g_{330}]\exp[(\beta+\gamma)z/c], \tag{3}$$

where $k_j(z)\,(j = 1{,}3)$ are the thermal conductivities, $c_{jl}(z)$, $e_{jl}(z)$ and $\varepsilon_{jj}(z)$ are the elastic constants, piezoelectric constants and dielectric permittivities, respectively, $\lambda_{jj}(z)$ are the temperature-stress coefficients, $g_{33}(z)$ is the temperature-electric displacement coefficient, δ, β and γ are the thermal conductivity gradient parameter, stiffness gradient parameter and thermal expansion gradient parameter, and k_{j0}, c_{jl0}, e_{jl0}, ε_{jj0}, λ_{jj0} and g_{330} are the reference values at the surface $z = 0$ of the graded piezoelectric layer.

The constitutive equations for the heat flux and the hyperbolic heat conduction equation with no internal heat generation are given by

$$q_x = -k_1\frac{\partial T}{\partial x} - \tau_q\frac{\partial q_x}{\partial t},\qquad q_z = -k_3\frac{\partial T}{\partial z} - \tau_q\frac{\partial q_z}{\partial t}, \tag{4}$$

$$-\frac{\partial q_x}{\partial x} - \frac{\partial q_z}{\partial z} = \rho C\frac{\partial T}{\partial t}, \tag{5}$$

where $q_l(x, z, t)\,(l = x, z)$ are the components of the heat flux, T denotes the temperature, ρ is the mass density, C is the specific heat, τ_q is the thermal relaxation time related to the collision frequency of the molecules within the energy carrier, and t is time variable. The initial temperature and thermal flux are assumed to be zero.

The constitutive equations for the stresses and electric displacements are given by

$$\begin{aligned}\sigma_{xx} &= c_{11}\frac{\partial u}{\partial x} + c_{13}\frac{\partial w}{\partial z} + e_{31}\frac{\partial \phi}{\partial z} - \lambda_{11}T\\ \sigma_{zz} &= c_{13}\frac{\partial u}{\partial x} + c_{33}\frac{\partial w}{\partial z} + e_{33}\frac{\partial \phi}{\partial z} - \lambda_{33}T,\\ \sigma_{xz} &= c_{44}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) + e_{15}\frac{\partial \phi}{\partial x}\end{aligned} \tag{6}$$

$$\begin{aligned}D_x &= e_{15}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) - \varepsilon_{11}\frac{\partial \phi}{\partial x}\\ D_z &= e_{31}\frac{\partial u}{\partial x} + e_{33}\frac{\partial w}{\partial z} - \varepsilon_{33}\frac{\partial \phi}{\partial z} + g_{33}T.\end{aligned} \tag{7}$$

The equilibrium equations and the Gauss law take the following forms

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} = 0,\ \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} = 0, \tag{8}$$

$$\frac{\partial D_x}{\partial x} + \frac{\partial D_z}{\partial z} = 0, \tag{9}$$

where u and w are the mechanical displacements, ϕ is the electric potential, σ_{xx}, σ_{zz} and σ_{xz} are the stress components, and D_x and D_z are the electric displacement components.

Substituting Eqs. (4), (6) and (7) into Eqs. (5), (8) and (9) with considering Eqs. (1)–(3), one has

$$k_0\frac{\partial^2 T}{\partial x^2} + \frac{\delta}{c}\frac{\partial T}{\partial z} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{D_3}\frac{\partial T}{\partial t} + \frac{\tau_q}{D_3}\frac{\partial^2 T}{\partial t^2}, \tag{10}$$