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Thermoelastic analysis of a partially insulated crack in a strip under thermal impact loading using the hyperbolic heat conduction theory

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ABSTRACT

In this paper, the transient temperature and thermal stresses around a partially insulated crack in a thermoelastic strip under a temperature impact are obtained using the hyperbolic heat conduction theory. Fourier and Laplace transforms are applied and the thermal and mechanical problems are reduced to solving singular integral equations. Numerical results show that the hyperbolic heat conduction parameters, the thermal conductivity of crack faces, and the geometric size of the strip have significant influence on the dynamic temperature and stress field. The results based on hyperbolic heat conduction show much higher temperature and much more dynamic thermal stress concentrations in the very early stage of impact loading comparing to the Fourier heat conduction model. It is suggested that to design materials and structures against fracture under transient thermal loading, the hyperbolic model is more appropriate than the Fourier heat conduction model.

1. Introduction

The use of heat sources such as laser and microwave with extremely short duration or very high frequency has found numerous applications for purposes such as surface melting of metal and sintering of ceramics (Tang & Araki, 1996). Recently, very strong substrate/coating interfaces have been obtained via using pulsed laser coating of bioceramic/metal nanomaterials on metal substrates by Zhang and Cheng (2011). In such situations the Fourier heat conduction model, which implies infinite thermal wave propagation speed, becomes inaccurate. Experiments show that the measured surface temperature of a thin structure immediately after an intense thermal shock by pulsed laser heating is 300 °C higher than that obtained from the parabolic heat conduction model (Babaei & Chen, 2008; Maurer & Thompson, 1973).

Thermal stress problems occur in many branches of engineering and have received considerable attention both in analysis and design. Many structural components are subjected to severe thermal loading which can give rise to intense thermal stresses in the components, especially around cracks and other defects. Micro-cracks have shown to have a pronounced effect on the effective thermal conductivities of the plasma-sprayed ceramic coatings (Sevostianov & Kachanov, 2000). Some materials become brittle when thermal stresses appear quickly as the result of a high temperature gradient in an unsteady temperature field. The thermal stresses alone or in combination with mechanical loadings can give rise to cracks and rupture in components containing brittle materials, and the concentration of stresses around defects often results in catastrophe (Kovalenko, 1969).

The study of the distribution of thermal stress in the vicinity of a crack in an elastic body has been extensively performed since 1950s by using the classical Fourier heat conduction theory (Lee & Shul, 1991; Sih, 1962; Tsai, 1984; Williams, 1959). If

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the effects of both the inertial term and the thermoelastic coupling term are neglected, the concept of superposition can be applied to solve the thermoelastic fracture problem (Nied & Erdogan, 1983). More general coupled thermoelastic theories have been adopted to study the fracture problems in thermoelasticity (Atkinson & Craster, 1992; Chen & Weng, 1991). In most of the usual engineering applications it is proper to use the uncoupled thermoelastic theory without significant error (Boley & Weiner, 1985; Noda, Matsunaga, & Nyuko, 1990).

Numerous studies have been devoted to solving crack problems under thermal loading in functionally graded materials based on the classical Fourier heat conduction model (El-Borgi, Erdogan, & Hidri, 2004; Erdogan & Wu, 1996; Itou, 2004; Noda & Jin, 1993; Ueda, 2008; Wang & Mai, 2005; Zhou, Li, & Yu, 2010). Qin (2000) obtained the General solutions for thermopiezoelectrics with various holes under thermal loading. Gao and Noda (2004) investigated the thermal-induced interfacial cracking of magnetoelectroelastic materials.

The Fourier heat conduction model, although giving sufficient accuracy for many engineering application, implies infinite thermal wave propagation speed, which is physically impossible, and is ineffective at the very small length and time scales associated with small-scale systems (Babaei & Chen, 2010; Hector, Kim, & Oisik, 1992). For many technological applications that involving high thermal energy with extremely short time, the results predicted by using the Fourier heat conduction model differ significantly from the experimental results (Al-Nimr, 1997; Tzou, 1990a). Ostoja-Starzewski (2009, 2011) examined the governing equation of hyperbolic thermoelasticity from the free energy and dissipation potentials. Consideration of the hyperbolic heat conduction model becomes important if irreversible physical processes, such as crack or void initiation in a solid, are involved in the process of heat transport. In these cases, the hyperbolic heat conduction model should be used (Al-Khairy & Al-Ofey, 2009; Tzou, 1989).

A few investigations on thermal stresses around cracks in thermoelastic materials have been made using the hyperbolic heat conduction model. Among them are Manson and Rosakis (1993a, 1993b), who derived a solution of the hyperbolic heat conduction equation for a traveling point heat source around a propagating crack tip, and measured the temperature distribution at the tip of a dynamically propagating crack experimentally. Tzou (1990b) investigated the near-tip behavior of the thermal field around a moving crack and studied the effect of crack velocity on the properties of the thermal shock. A thermoelastic analysis of a cracked half-plane under a thermal shock impact was recently given by Chen and Hu (2011) based on the hyperbolic heat conduction theory.

To the author's knowledge, the partially insulated crack problem in a thermodynamic strip considering both partial insulation of the crack faces and the hyperbolic heat conduction model has not yet been reported in the literature. In this paper, we analyze the transient temperature and thermal stresses around a crack in a thermoelastic strip under a temperature impact loading using the hyperbolic heat conduction theory. The crack lies parallel to the free surface under plane elasticity conditions and the crack faces are assumed to be partially thermal insulated. Fourier transforms are employed to derive the singular integral equations about the temperature and the thermal stress field. Dynamic temperature and stress field around the crack are obtained by solving singular integral equations numerically using asymptotic analysis. Laplace inversion is applied to get the temperature and stress fields in the time domain. The effect of the parameters of the hyperbolic heat conduction model, the geometric size of the strip and the partially thermal conductivity of the crack faces on the disturbance field are investigated numerically. The results based on hyperbolic heat conduction show much more dynamic thermal stress concentrations in the very early stage comparing to the Fourier heat conduction model.

2. Statement of the problem and basic equations

To deal with the damage problems of thin structures under high energy thermal loading, such as pulsed laser heating on a coating, accurate heat conduction analysis is of great importance for the material and structural integrity. We consider an elastic strip under transient thermal loading, and the strip contains a crack of length $2c$ parallel to the free surface, as shown in Fig. 1, where $H()$ is the Heaviside unit step function. The strip is initially at the uniform temperature zero, and its free surface, $y = -h_a$ and $y = h_b$ are suddenly heated to temperature T_a and T_b, respectively. The crack surfaces are assumed to

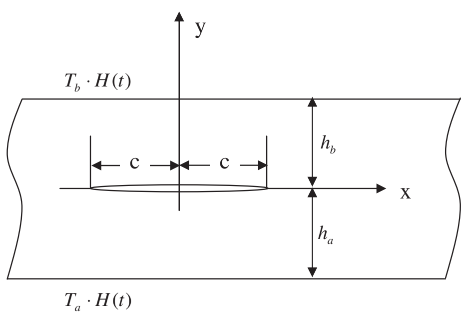

Fig. 1. Crack geometry and coordinates.